FIBER-OPTIC UNDERSEA TOW CABLE OPTICAL AND ENVIRONMENTAL TESTS

WH PUTNAM

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Test and Evaluation, April to December, 1976

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Tests of two fiber-optic cables revealed that fibers for communication purposes can be incorporated into tow cables with very little excess loss during manufacture. Further development in cable design and fiber buffers is required to eliminate excess loss when cables are subjected to tension, temperature, and pressure.

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OBJECTIVE

Test two fiber-optic undersea tow cables for changes in optical attenuation caused by cabling, tension, temperature, and pressure.

RESULTS

ITT CABLE

A six-fiber cable, manufactured by ITT/Electro-Optical Products Division, had optical attenuations of 5 to 13 dB/km at 820 nm prior to cabling and 5 to 14 dB/km after cabling. The maximum attenuation increase was 1.4 dB/km; one fiber decreased 2.4 dB/km (possibly due to improper measurement conditions prior to cabling). The two graded-index fibers had dispersions (pulse spread) of less than 1 ns (520-m length). Each fiber was proof-tested to 1% elongation over the entire length prior to cabling. The attenuation of a graded-index fiber increased when subjected to tension (10 dB/km at 67 kN* [15 klb]), temperature (1.5 dB/km at 1°C), and pressure (0.4 dB/km at 69 MPa* [10 kpsi]).

SIMPLEX CABLE

A three-fiber cable, manufactured by Simplex Wire and Cable Company, had optical attenuations of less than 5 dB/km at 820 nm prior to cabling and 120 to 570 dB/km after cabling [the increase is attributed to microbend loss caused by inadequate fiber buffers]. The three Corning Glass Works step-index fibers had 20 ns dispersion (500-m length). The fibers were not proof-tested for strength before cabling. They were estimated by Corning to have 0.2% elongations to break. The Simplex cable was not tested for tension effects because of fiber breakage. The attenuation of a step-index fiber increased when subjected to temperature (over 100 dB/km at 1°C) and pressure (176 dB/km at 69 MPa). During both tests, the monitored fiber broke (at 63°C and 69 MPa, respectively).

CONCLUSIONS

1. The test results of these cables, which were the first two fiber optic cables developed for undersea applications, established the feasibility of using fiber optics in undersea tow cables.
2. As demonstrated by the ITT cable, optical fibers can be cabled with very low attenuations. Three fibers had less than 6 dB/km attenuations at 850 nm, but tension- and temperature-induced attenuation increases severely limit use of the cable in the undersea operational environment.

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*The S.I. metric unit of force is the newton (N); the unit of pressure is the pascal (Pa).

RECOMMENDATIONS

1. Develop a follow-on cable using the experience gained in the development of the first cables and recent improvements in:

a. fiber attenuation, dispersion, numerical aperture, and strength, and

b. cable design, buffering techniques, and cabling machinery.

These factors are expected to significantly reduce or remove all noted cable deficiencies.

2. Continue the fiber strength and fatigue improvement program supported by the Defense Advanced Research Projects Agency (DARPA).

ADMINISTRATIVE INFORMATION

The tests were conducted by WH Putnam of the Command and Control Branch, EO/Optics Division of the Naval Electronics Laboratory Center (NELC) between 1 April and 3 December 1976. These tests were sponsored by DARPA and were performed under Program Element 61101, Task Area OSD, NELC F231. The cable developments, sponsored by DARPA and the Naval Electronic Systems Command, were conducted under NELC contract N00123-75-1023 (ITT EO Products Div.) and Naval Undersea Center (NUC) contracts N66001-75-C-0033 (Corning Glass Works), N66001-75-C-0045 (Air Logistics Corp.), and N66001-75-C-1030 (Simplex Wire and Cable Co.). The NELC manager of the Fiber Optic Undersea Cable Program is RA Eastley, who established the test plan and coordinated testing procedures. GA Wilkins, NUC code 06532, Hawaii, designed the Simplex cable, evaluated the mechanical design of the ITT cable, and mechanically tested both cables. This report was approved for publication 20 December 1976.

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INTRODUCTION

The task reported upon in this report is part of the Fiber-Optic Undersea Cable Program in which fiber-optic cables are being developed for undersea applications. Since 1973, when the first long fiber (3 km, 3 dB/km at 820 nm) was delivered to NELC, a number of experimental cable prototypes have been developed and evaluated for tow, bottom-laid, sonobuoy, and torpedo applications. These represent the first known attempts to package optical fibers for use in the severe undersea environment.

The 2 cables evaluated under this task were tested for changes in optical attenuation induced by tension, temperature, and pressure. One of the cables was developed by ITT/Electro-Optical Products Division (ITT/EOPD) and incorporated 6 ITT/EOPD optical fibers which were ruggedized by ITT/EOPD and cabled at ITT/Hydrospace (figures 1 and 2). The second cable was developed at Simplex Wire and Cable Company and incorporated 3 optical fibers manufactured by Corning Glass Works (figure 3). These fibers were packaged in an optical subunit by Air Logistics Corporation prior to being cabled.

The ITT cable was designed and developed by ITT under NELC contract N00123-75-C-1023 and was delivered in June 1976. The Simplex cable was designed by GA Wilkins of the Naval Undersea Center (NUC), Hawaii, and was delivered in October 1975. The Simplex cable optical subunit was fabricated by Air Logistics Corporation under NUC contract N66001-75-C-0045 and the tow cable was fabricated by Simplex under NUC contract N66001-75-C-0103. Both cables were developed and tested as prototypes in order to obtain the benefits of fiber optics in undersea cables. They were designed to the specifications shown in table 1.

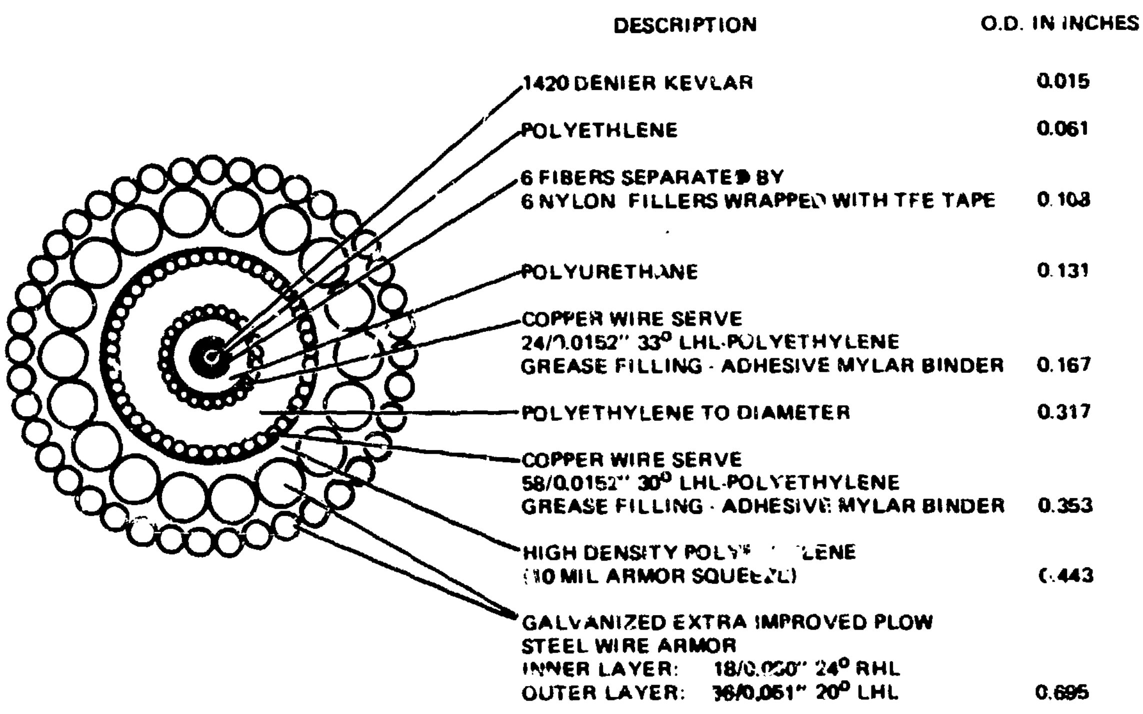


Figure 1. ITT tow cable.

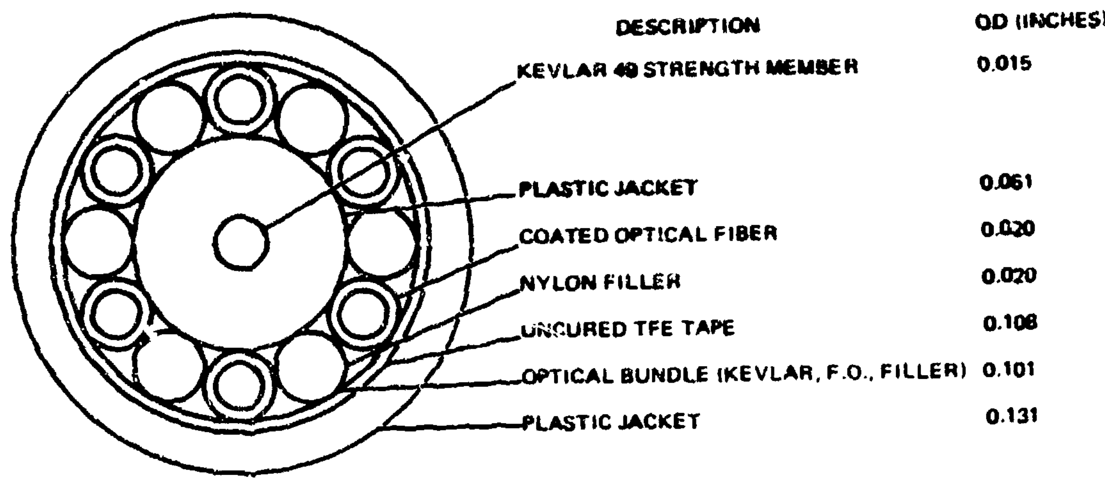


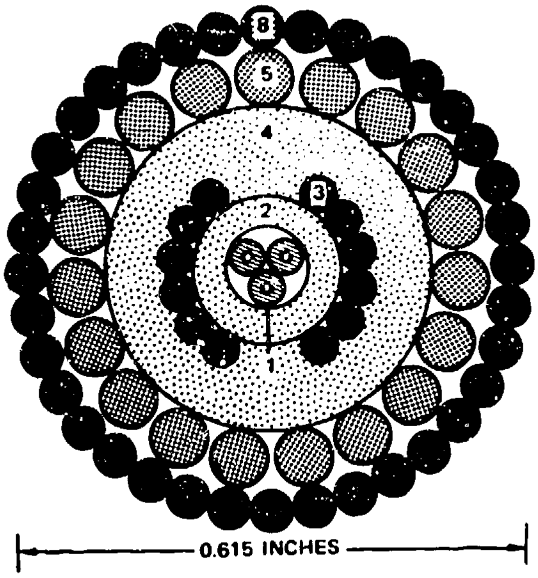
Figure 2. Optical subunit for ITT tow cable.

TABLE 1. TOW-CABLE SPECIFICATIONS.

MECHANICAL	
Length	500 metres
Diameter	1.77 cm (0.697 inch)
Breaking Strength	147 kN (33 000 lbs)
Weight in air	10 N/m (750 lbs/1000 ft)
Torque balanced	
Nonhosing	
ELECTRICAL	
Conductors	3000 V, 10 A, 60 Hz
Breakdown test	10 kV, 60 Hz
Loop resistance	10 ohms/km (3.05 ohms/1000 ft)
OPTICAL	
Number of fibers	6 (4 step, 2 graded)
Attenuation	<15 dB/km at 0.82 micrometre
Numerical aperture	>0.1
Pulse dispersion	<10 ns/km

TABLE 1. (Continued)

ENVIRONMENTAL	
Operating temperature	(25°F to 90°F) (-4°C to +32°C)
Stowage temperature	-80°F to +167°F (-62°C to +75°C)
Seawater operation	
Pressure	69 MPa (10 000 psi)



CABLE COMPONENTS:

(1) OPTICAL FIBER BUNDLE, 3 FIBERS, 0.097 INCH DIAMETER,
(2) FIRST ELECTRICAL JACKET; AN EXTRUSION OF SUBMARINE-CABLE GRADE, LOW-DENSITY, HIGH-MOLECULAR-WEIGHT, POLYETHYLENE,
(3) 12 HARD-DRAWN COPPER WIRES (97% CONDUCTIVITY), EACH 0.040-INCH OD, AS TWO 6-WIRE CONDUCTORS,
(4) SECOND ELECTRICAL JACKET, EXTRUDED OF SAME MATERIAL AS ITEM 2,
(5) FIRST ARMOR LAYER; 19 WIRES OF 300000-PSI CABLING STEEL, EACH 0.060-INCH OD, AND
(6) SECOND ARMOR LAYER; 36 WIRES OF 300000 PSI CABLING STEEL, EACH 0.047-INCH OD.

Figure 3. Simplex tow cable.

Special equipment and fixtures were developed for environmental and mechanical evaluations of fiber-optic cables. These equipments included sensitive optical monitoring devices to measure small attenuation changes during environmental tests of cables as short as 33 metres, and a fiber-optic pressure feedthrough capable of withstanding 69 MPa (10 kpsi). Optical measurement facilities and techniques were improved and methods for stripping cables without damaging the optical fibers were investigated. Tests were conducted in accordance with the test plan shown in table 2. The results presented in this report are based on single cable samples per test, not statistical samples.

TABLE 2. TEST PLAN.

<u>OPTICAL EVALUATION</u>

Initial test

Spectral attenuation

Numerical aperture

Pulse dispersion

Optical isolation between fibers

<u>MECHANICAL TESTING</u>

Tension

<u>ENVIRONMENTAL TESTS</u>

Temperature cycling

Dimensional stability at elevated temperature

Thermal shock and cold bend

Hosing (axial leakage) under pressure

Pressure

The optical tests were performed first over the entire cable lengths. The cables were then cut into sections, 50 to 100 metres in length, for additional mechanical and environmental tests. The additional mechanical tests were performed at Tension Member Technology Division (TMT) of Philadelphia Resins under a NUC contract. The results of the additional mechanical test will be reported separately by TMT ("Fiber Optic Tow Cable Mechanical Tests", in preparation).

OPTICAL EVALUATION TESTS

INITIAL TEST

The cables were inspected visually for kinked wires, crossovers, and imperfections and were checked for optical continuity on the reel. Electrical resistance checks were made of each conductor, between conductors, and between conductors and the armor wires on the ITT cable (the Simplex cable conductors shorted during manufacture).

SIMPLEX CABLE

No imperfections were apparent in the armor of the Simplex cable. No galvanized steel armor wires were available during manufacture of this cable; the delivered cable had unprotected wires which rusted. The cable was checked several times on the reel for optical transmission using 8 sources of increasing power. Ultimately, a 1-mW, HeNe laser and a lens were used to couple light into each of the fibers. No transmission was observed, indicating an attenuation of at least 100 dB/km.

Work was begun on the development of an optical time-domain reflectometer for use in locating breaks in the optical fibers. Subsequent measurements of the spectral attenuation of a 95-metre section of the cable indicated that the poor transmission was caused by attenuation increases during the manufacture of the cable rather than by breaks in the fibers. Electrical resistance checks were not made; during manufacture, the copper wires had shorted together.

ITT CABLE

The armor of the ITT cable showed no apparent imperfections. The cable was exposed to weather for several months and showed no signs of degradation. The continuity of the cable was checked on the shipping reel using a penlite. All fibers transmitted light. Electrical resistance was measured over the full 520-metre length using a Fluke model 8120 multimeter. The results are listed in table 3.

TABLE 3. ITT CABLE D-C RESISTANCE (520 m).[1]

	NELC Measurement	ITT Measurement	Specification
Outer conductor, ohms	1.6	1.64	
Inner conductor, ohms	4.2	4.47	
Loop resistance, ohms	5.8	6.11	5.2

Resistance between each conductor, between conductors, and between conductors and the armor wires was as expected (>10 megohms).

The outer diameter of the ITT cable was larger than specified; 1.80 cm compared to 1.77 cm. The diameter was expected to reduce slightly after initial loading, but not enough to bring it into specification. The 1.4 percent of extra diameter could cause excessive wear on the cable were it to be used on sheave wheels designed to the specification.

[1] ITT/Electro-Optical Products Division Final Report, Contract N00123-75-C-1023, 300-Metre Sonobuoy Cable, 500-metre Tow Cable, by R Freiberger, July 1976.

SPECTRAL ATTENUATION

The optical attenuation of each fiber was measured at eleven discrete wavelengths between 500 and 1050 nm with the cable on the reel and unreeled (strung). The purpose was to verify the specified attenuation for contractual purposes (15 dB/km for the ITT cable at 820 nm) and to predict behavior of the cable with optical sources operating at wavelengths other than 820 nm. Spectral attenuation was measured on the full 520-metre ITT cable, reeled and strung, and on 95 metres of the Simplex cable. One of the Simplex fibers, because of high attenuation, was measured using a HeNe laser.

DATA

Spectral-attenuation measurements are presented in table 4 and in figures 4 and 5. The ITT data are included for completeness.[1] The measurements made by NELC and ITT/EOPD are estimated to have a precision of ±0.5 dB/km, based upon similarity of equipments. The equipment available at ITT/CHD was less sophisticated; precision is estimated to be ±50 percent of the tabulated values.

RESULTS

The ITT tow cable surpassed the optical specification of 15 dB/km at 820 nm. The cable had less than 1.5 dB/km excess cabling loss* in the strung (out straight) condition and an average attenuation of 8 dB/km. Fiber 6N appeared to be sensitive to bending strain as its attenuation dropped 8 dB/km from the reeled to the straight condition.

For the step-index fibers (1N, 2N, 3N, 6N) the attenuation minima occurred at source wavelengths of 900 and 1050 nm. For the graded-index fibers (4N, 5N), there was clearly no optimum wavelength because of the lack of an absorption peak at 950 nm.** The Simplex cable had severe microbend losses. Its spectral attenuation curves, which are unusual compared to low-loss fibers, exhibit increased attenuation at longer wavelengths.

NUMERICAL APERTURE

The numerical aperture is defined to be

$$NA = (n_1^2 - n_2^2)^{1/2}$$

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*Excess cabling loss is the increase in fiber attenuation which occurs during cable manufacture. ITT/EOPD performed the attenuation measurements of the optical fibers before cabling while the fibers were wound on 10-cm diameter spools rather than strung. Because of winding tension and the number of fiber-to-fiber crossovers (small radius bends) which occurred on the small spools, some excess loss was probably included in the "before" measurements; the attenuation of fibers 1N and 6N decreased during cabling. The highest measured cabling loss was 1.4 dB/km for fiber 2N

**Step-index fibers exhibit an abrupt change in refractive index at the core/clad interface; graded-index fibers exhibit a gradual change in refractive index, reaching a maximum at the center of the core

TABLE 4. ITT CABLE ATTENUATION AT 820 nm.

A. ITT CABLE

			ITT/EOPD			ITT/CHD					NELC
NELC* Fiber Number	ITT Fiber Number	Type Index	Fibers Before Cabling 700 m dB/km	Optical Subbundle 689 m dB/km	Before First Serve dB/km	After First Serve dB/km	After Dielectric dB/km	After Coax Jacket dB/km	First Measurement dB/km	Second Measurement dB/km	On Reel/ Strung 520 m dB/km
1N	5	Step	6.6	5.7	7.8	15.0	10.2	15.7	12.2	7.5	5.2/5.8
2N	4	Step	7.3	8.0	8.8	6.0	8.8	6.2	7.2	11.0	8.1/8.7
3N	3	Step	6.8	8.0	8.8	7.0	6.6	7.4	7.4	8.5	8.3/7.0
4N	2	Graded	12.3	17.3	17.2	24.0	12.7	16.1	11.4	15.0	12.9/13.6
5N	1	Graded	5.3	6.8	10.5	11.2	7.2	15.6	15.4	15.0	5.6/5.6
6N	6	Step	10.1	9.1	11.4	13.1	9.8	14.5	13.7	8.5	15.5/7.7

*Fibers were not identified on cable by ITT. NELC numbers were assigned when the cable arrived and subsequently were verified by dispersion measurements.

B. SIMPLEX CABLE

		CORNING	NELC		
NELC Fiber ID	Corning ID	Fibers Before Cabling 500 m dB/km	Optical Subunit on 50-cm Reel 466 m dB/km	Optical Subunit on 100-cm Reel 466 m dB/km	After Cabling Strung 95 m dB/km
Black	17	4.9	28	23	120
White	18	4.4	72	31	450
Red	16	4.6	no trans.	no trans.	570

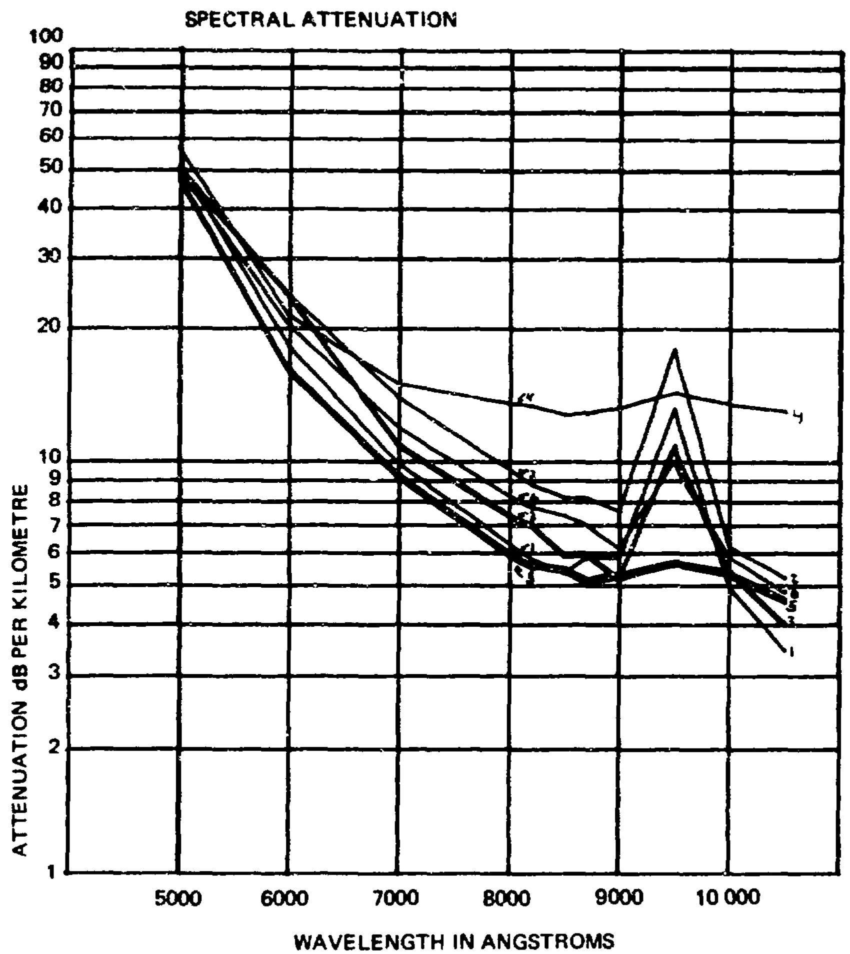

Figure 4. ITT cable spectral attenuation.

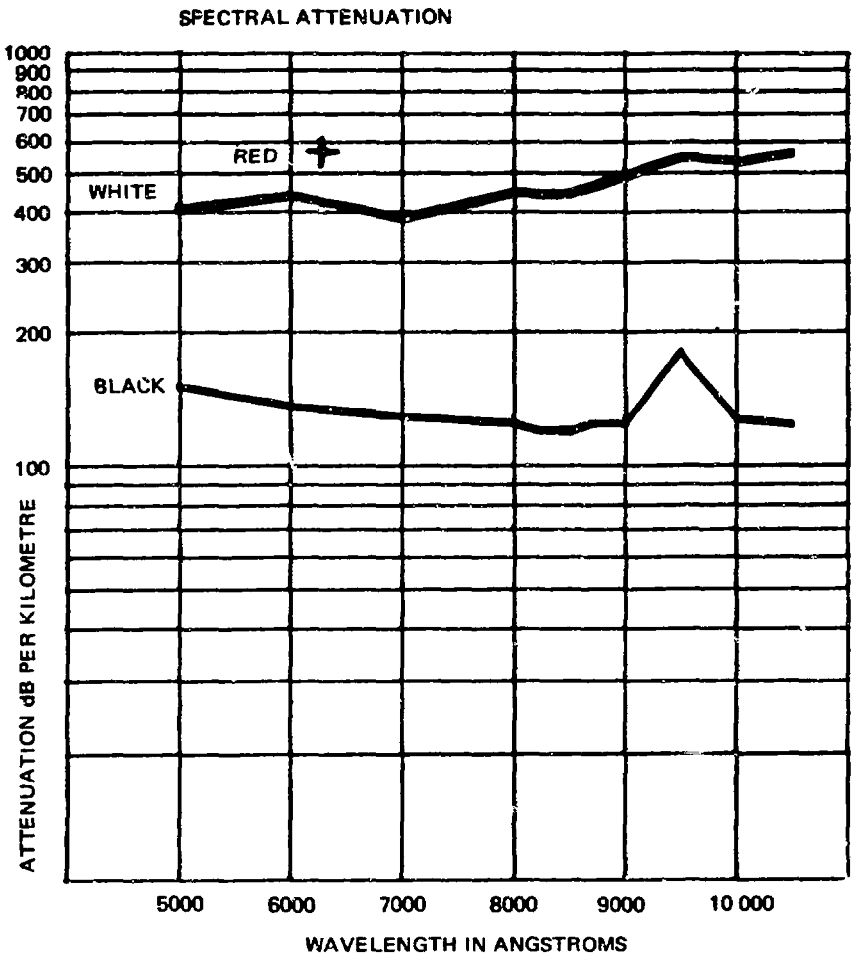

Figure 5. Simplex cable spectral attenuation.

where

NA = numerical aperture

n_1 = index of refraction of optical core

n_2 = index of refraction of optical clad

A measurement of numerical aperture is the sine of the half-angle between points 10 dB below the peak intensity of light emerging from an optical fiber when light is launched at an angle greater than the NA. The numerical aperture of the fiber is an indication of the fiber's light-gathering power; a 0.25-NA fiber accepts more light than does a 0.15-NA fiber from a diffuse source. In addition, high NA fibers are less susceptible to microbends.[2,3] It is reasonable to expect, therefore, that the graded-index fibers, which have lower numerical apertures, are more susceptible to microbends than step-index fibers having high numerical apertures.

DATA

Numerical aperture was not measured on the Simplex cable because there was insufficient signal over the 95-metre section to determine the angular pattern. The NA, measured by Corning before cabling, was 0.186 for all 3 Simplex fibers. The data for the ITT fibers are presented in table 5 and figure 6.

TABLE 5. ITT CABLE NUMERICAL APERTURE.

Fiber	On Reel	Straight
1N	0.24	0.23
2N	0.28*	0.24
3N	0.23	0.25
4N	0.14	0.15
5N	0.15	0.16
6N	0.20	0.19

* Possible measurement error; precision is 0.01.

RESULTS

The fibers in the Simplex cable had an NA of 0.186, whereas the fibers in the ITT cable ranged from 0.15 to 0.25. The ITT contract specification was for a NA of 0.10, minimum. There appears to be a small NA increase in the straight ITT cable over that of the reeled. It is possible that the fibers in the reeled cable, which were under

[2] Olshansky, R, "Distortion Losses in Cabled Optical Fibers," Applied Optics, v 14, no 1, January 1975

[3] Gardner, WV, "Microbending Losses in Coated and Uncoated Optical Fibers," Optical Fiber Transmission Topical Meeting, 7 to 9 January 1975, Williamsburg, VA

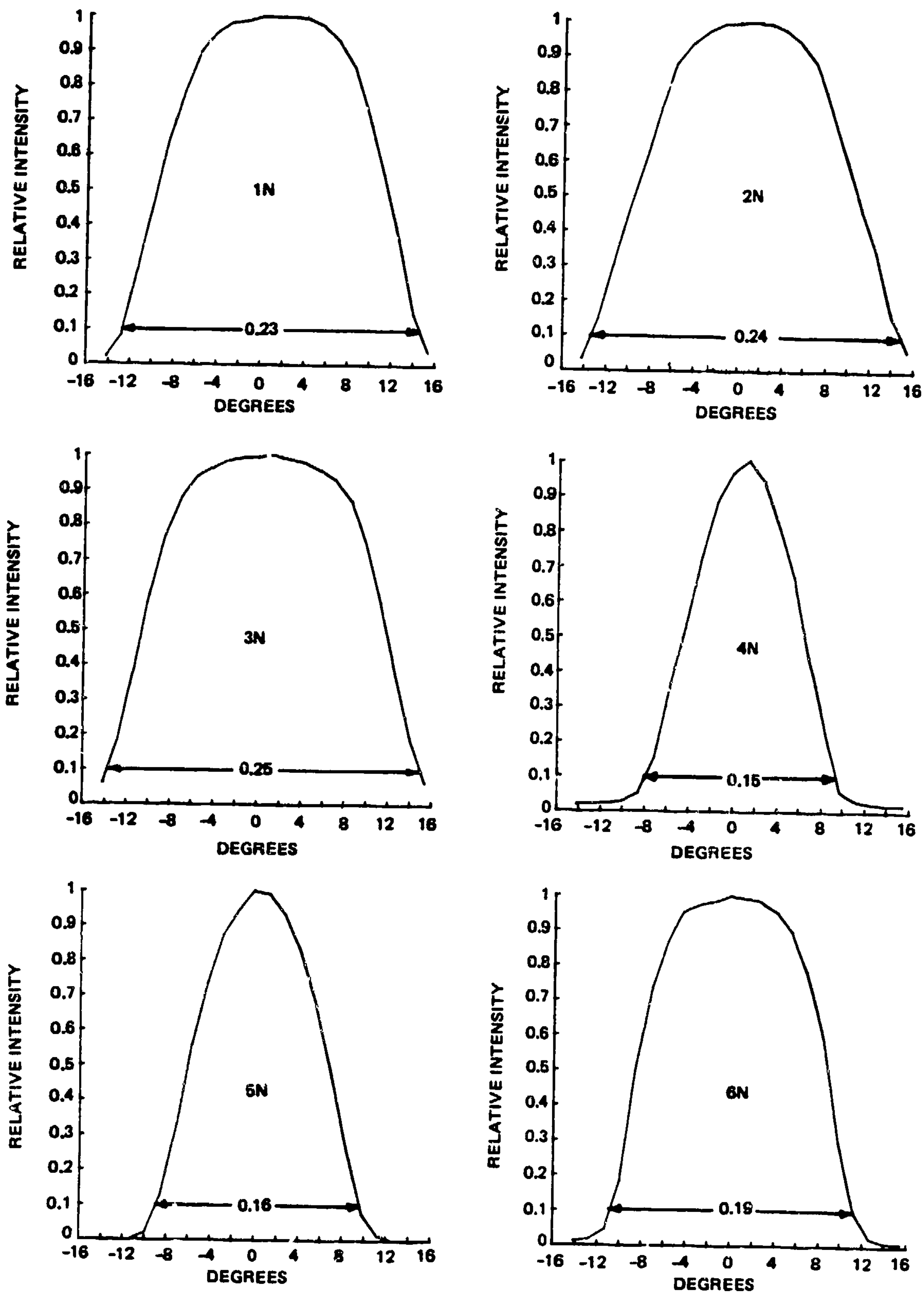

Figure 6. ITT cable numerical aperture.

more stress than those in the straight cable, propagated light in a narrower range of modes; higher-order (larger angle from fiber axis) modes are radiated in stressed fibers.[2,3]

DISPERSION

Dispersion is the amount of pulse spreading introduced by the fiber (measured between points 10 dB below the peak) which determines the bandwidth of the transmitted signals. The Simplex cable contained 3 step-index (high-dispersion) fibers. The ITT cable contained 4 step-index and 2 graded-index (low-dispersion) fibers. Although it is not possible to predict accurately the performance of relatively short fibers, scaled out to several kilometres, the dispersions which were measured in the tests will form a basis of comparison with similar-length fibers and constitute an upper bound on the expected dispersion at the longer lengths.

DATA

The dispersions of the ITT fibers are presented in table 6 and figures 7 and 8. Precision of the data for step-index fibers (1N, 2N, 3N, 6N) is ±10 percent. The shape of the output pulse depends upon several factors which include input and output coupling. A lower dispersion (shorter pulse) will be measured if the input laser pulse is not focussed to fill the fiber numerical aperture or if the detector does not accept all the emerging light. It is possible that these conditions occurred during the NELC measurement of fiber 1N (on reel) and during the ITT measurements.

TABLE 6. ITT CABLE DISPERSION, ns/km

NELC ID	NELC On Reel 3dB	NELC On Reel 10dB	NELC Straight 3dB	NELC Straight 10dB	ITT On Reel 3dB	ITT On Reel 10dB	Theoretical Dispersion*	ITT ID
1N	8	23	19	54	6	12	61	5
2N	13	40	13	50	7	12	66	4
3N	15	56	15	50	10	16	72	3
4N	2	3	2	2	0.8	1.5	26	2
5N	1	3	1	2	0.8	1.4	29	1
6N	15	54	15	40	9	16	41	6

*Theoretical dispersion is based on the time-of-arrival difference between light propagating in the core and in the clad of a step-index fiber.

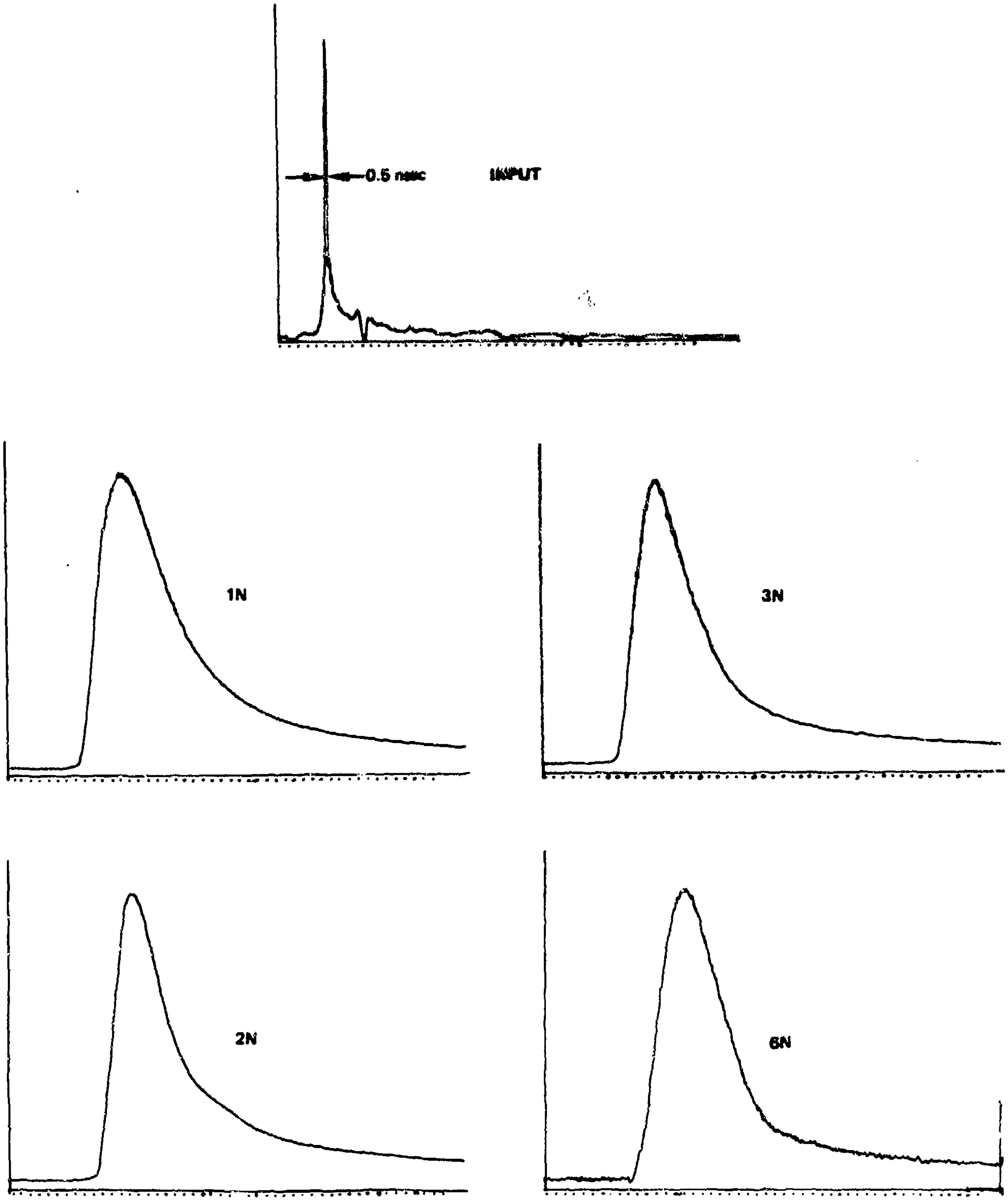

Figure 7. ITT cable dispersion, step-index fibers, 1 nsec/div, 520m.

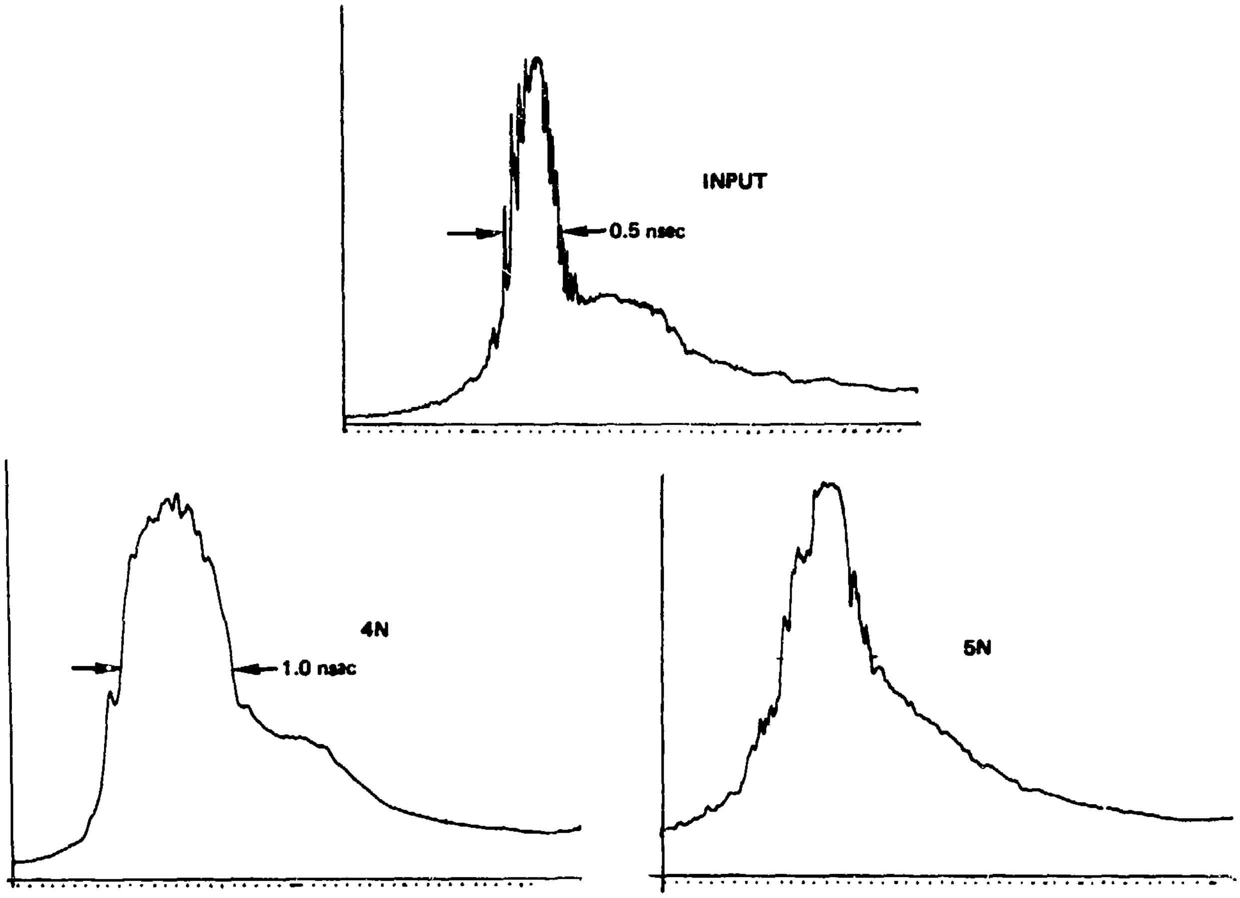

Figure 8. ITT cable dispersion, graded-index fibers, 0.1 nsec/div, 520m.

Dispersion in step-index fibers can be estimated theoretically, based upon the difference in group velocities for light propagating in the core and clad at c/n_1 and c/n_2 respectively, where c is the speed of light in a vacuum. Since numerical aperture is also related to the indices of refraction, an expression can be written for dispersion $\Delta t/L$ in terms of the NA:

$$\Delta t/L = (n_1 - n_2)/c$$

$$NA = (n_1^2 - n_2^2)^{1/2}$$

Substituting,

$$\Delta t/L = NA^2/c\,(n_1 + n_2)$$

for doped silica fibers, $n_1 \approx n_2 = 1.45$, or

$$\Delta t/L = 1150\ NA^2$$

where dispersion is measured in ns/km.

The values for theoretical dispersion listed in table 6 are based on the measured NAs (straight). There is close agreement between the NELC step-index dispersions (10 dB) and the theoretical dispersions.

The precision of the NELC graded-index fiber dispersions is ±50 percent. The source of error is the slow component of the detector response. Referring to figure 8, the input pulsewidth, at 10 dB below the peak, is nearly as long as the output pulsewidths. Because of the small difference between output and input pulsewidths, the measured values represent upper bounds. The ITT data were taken with a detector which did not exhibit the slow response component; it is likely that the ITT measured values are more precise than the NELC values.

Dispersion was not measured on the 95-metre section of Simplex cable because insufficient signal was available. (Dispersion was measured previously at NELC on the optical fibers prior to cabling; the measured and theoretical dispersions were, respectively, Black, 30 and 40, White, 36 and 40, and Red, 40 and 40 ns/km at the 10-dB points below the peak.)

RESULTS

There are no significant differences between the data taken while the ITT cable was on the reel and those taken when it was straight. For the step-index fibers, the measured dispersion is approximately that predicted theoretically from the measured numerical apertures. For the graded-index fibers, the measured dipersions are at least a factor of 10 less than the theoretical dispersions of step-index fibers having the same NAs. The NELC contract specified that the dispersion be less than 10 ns/km for the graded-index fibers; the cable passed this specification.

OPTICAL ISOLATION

Crosstalk was measured in the ITT cable. The attenuation of the Simplex cable was too high to permit crosstalk measurements to be made. Two methods were used to measure crosstalk in the ITT cable; one was optical and the other was visual. With the optical method, a 1-mW HeNe laser was used to illuminate one fiber while a silicon PIN detector measured the light in each of the other 5 fiber t their near and far ends. With the visual method, the 5 nonilluminated fibers were observed through a 50X magnifier.

DATA AND RESULTS

No signal was observed, optically or visually, in the nonilluminated fibers of the ITT cable. Based upon measurements of input power and detector sensitivity, the crosstalk, if any, was more than 83 dB below input power.

MECHANICAL TEST

TENSION TEST

An optical test was devised during the NELC test program to measure the optical attenuation of a 50-m test sample loaded to the maximum design load of 147 kN (33 000 lb). This test was performed by NELC and TMT personnel at Coordinated Equipment

Company at Wilmington, California. The ITT cable was tested up to the equipment limit of 142 kN (32 000 lb). The Simplex cable was prepared for test but no transmission could be obtained apparently because of fiber breakage within the cable.

EQUIPMENT

The requirement that a long (50-m) sample of cable be tension-tested was met by conducting the test at Coordinated Equipment Company. The test bed used was 30 metres long and could exert a pull of over 1.4 MN (320 000 lbs) (figure 9). The 50-metre test sample ends were socketed in standard cable terminations (figure 10) which used an epoxy-filled cone to hold the armor wires; the cable core passed through the center of the termination. The test sample was pulled from its center over the 37-cm diameter sheave (pulley wheel) of the test bed. Cable elongation was monitored with a tape measure.

PROCEDURE FOR TENSION/ATTENUATION TEST

The ITT cable was tested first. After the cable terminations had been connected to the test bed using shackles, the 3-metre cable core ends were stripped back 2 metres. The buffered fibers were then connected to the optical monitoring devices within a small shelter.

Two fibers, one step-index (3N) and one graded-index (5N), were selected for optical monitoring. The tension was increased in 4.5 kN (1 klb) increments up to 62 kN (14 klb) and then decreased to zero. This process was repeated twice. The tension was then increased from 62 kN to 142 kN (32 klbs) and the attenuation was monitored. Elongation was monitored from 62 kN to 142 kN. The maximum tension was determined by the length of the stroke (elongation) available on the test bed. The small shelter served as a screen against the force of the cable in case of its breakage.

A test of the Simplex cable was not conducted. Both terminations of this cable were filled with epoxy too close to the end. When the cable was bent to clear the shackle, the fibers broke (figure 11). Subsequent tests revealed that the fibers were also broken within the cable, possibly at the point where they were bent around the 37-cm sheave. The 56-metre sample was cut from a 95-metre length of cable, previously measured at NELC to have 120 dB/km in the best fiber, prior to shipment to TMT for socketing and to Coordinated Equipment for tests. TMT was unable to find a continuous, 56-metre sample in the approximately 200 metres of cable shipped to them. This experience was similar to that of NELC; although 60-metre samples were prepared for the environmental pressure and temperature tests, they had to be cut to 33 metres in order to locate continuous fibers.

In lieu of conducting the Simplex cable test, the ITT cable was measured again by monitoring all available fibers. Fibers 5N and 6N were monitored at 22, 45, and 67 kN (5, 10, and 15 klbs) using 2 optical monitoring devices. Fibers 2N, 3N, and 1N were then monitored, one at a time because of a malfunction of a lock-in amplifier. Fiber 4N (the 14-dB/km initial attenuation graded-index) was too dim to monitor; its attenuation had increased dramatically during the three tension cycles on the previous day.

Figure 9. Tension test fixtures.
a. 30-m test bed

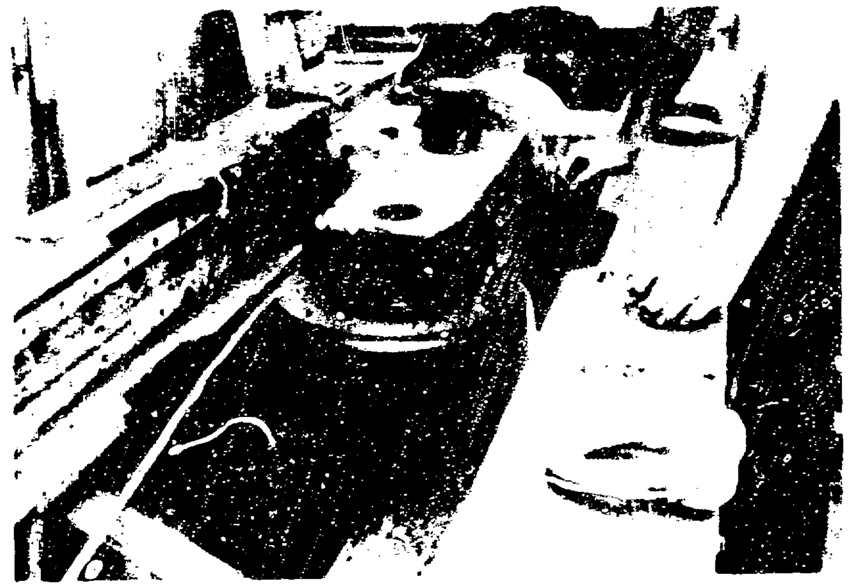

Figure 9. Continued. b. 37-cm diameter sheave

Figure 10. Cable termination for tension test. (The cable core passes through the center of the termination.)

Figure 11. Simplex cable termination. (The central core broke when it was bent to clear the shackle.)

DATA

The excess-loss data are presented in figures 12 through 17. The ITT cable was successfully tested to 142 kN (32 klbs) and neither of the two monitored fibers broke. It is possible that one of the two graded-index fibers (4N) broke during the first three cycles and that the other (5N) broke on the fourth. (Its attenuation had increased 28 dB/km by the end of the fifth cycle.) On the first three cycles, 5N had 9.5 dB/km of excess loss at 62 kN (14 klbs) and 40 dB/km at 142 kN (32 klbs). The step-index fibers had 0.5 (1N), 2.0 (2N), 1.5 (3N), and 4 dB/km (6N) excess loss at 67 kN (15 klbs). Fiber 3N had 2.5 to 5.0 dB/km excess loss at 142 kN (32 klbs).

The ITT cable had much lower measured cable modulus than predicted by ITT/Cable-Hydrospace Division. Preliminary results from TMT agree; a 4-metre section elongated 1.8 percent at 142 kN (32 klbs). Figure 18 indicates the elongation to be 1.85 percent at the same load. By comparison, the ITT/CHD predicted elongation of 0.98 percent. In the TMT test, all fibers broke at loads between 150 and 154 kN (33.2 and 34.2 klbs.).

The jacket of the ITT cable developed small holes (figure 19) at tension of approximately 62 kN (14 klbs). The holes developed initially at the 37-cm diameter sheave.*

During the tension tests, there was a small amount of drift in the optical monitoring devices. The curves for fibers 1N, 2N, 3N (cycle 4), and 6N were taken over a 15-minute period and drift was within 0.5 dB/km. The curves for fibers 3N (cycles 1-3) and 5N include some upward drift, probably 1.5 dB/km, over the test period.

*The small holes and the low cable modulus are related; subsequent analysis by TMT indicates that the inner armor layer cuts through the outer polyethylene jacket under tension. This allows the cable to stretch twice as much as calculated for an incompressible cable core. A harder plastic jacket, such as Hytrel, has been suggested by ITT as a possible solution

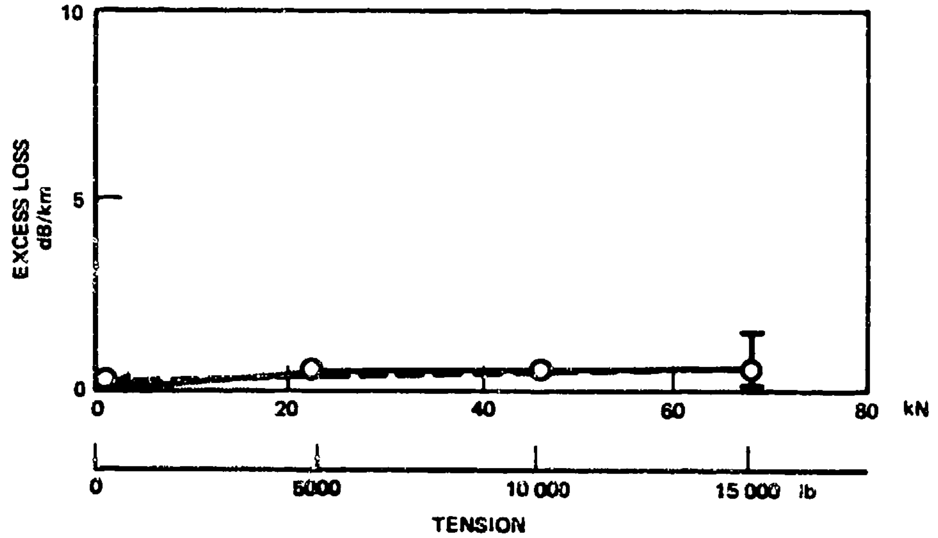

Figure 12. ITT cable tension tests, fiber 1N (step-index).

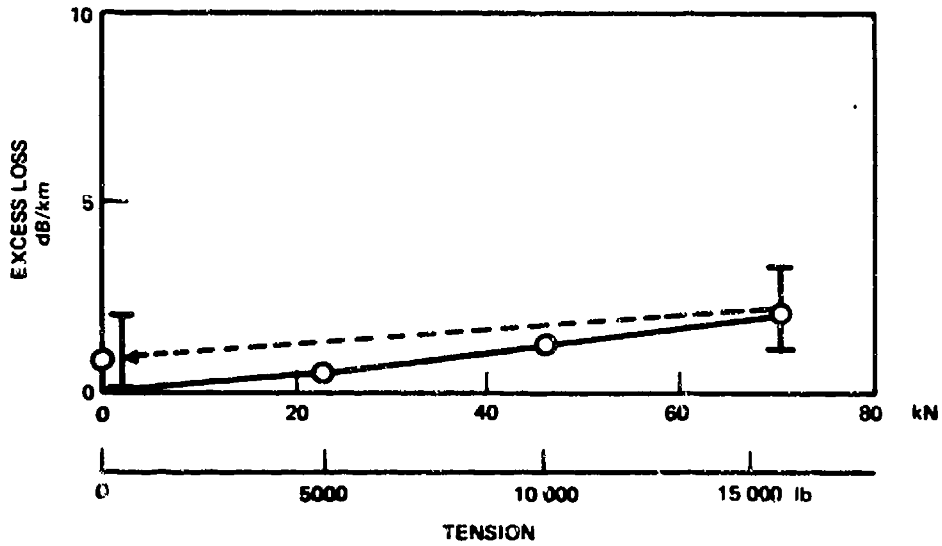

Figure 13. ITT cable tension test, fiber 2N (step-index).

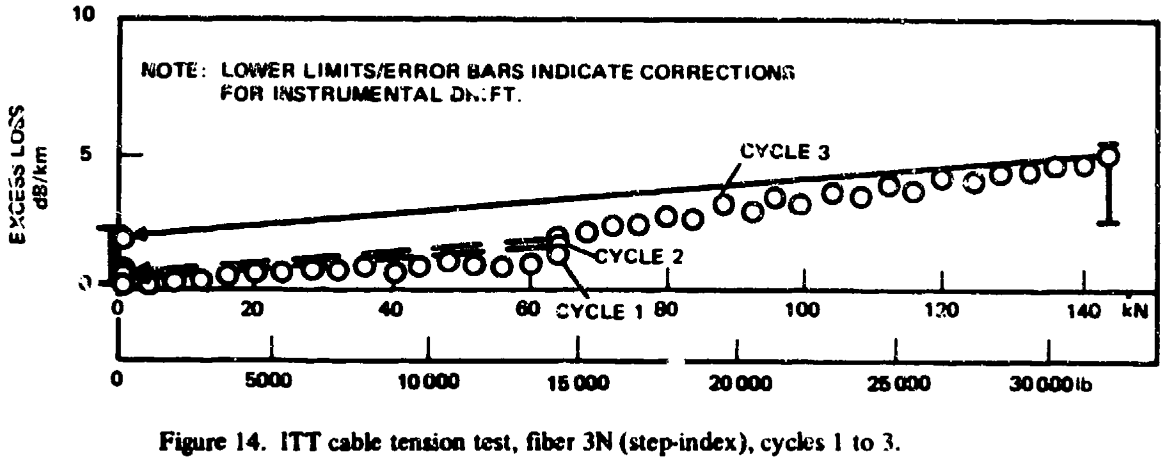

Figure 14. ITT cable tension test, fiber 3N (step-index), cycles 1 to 3.

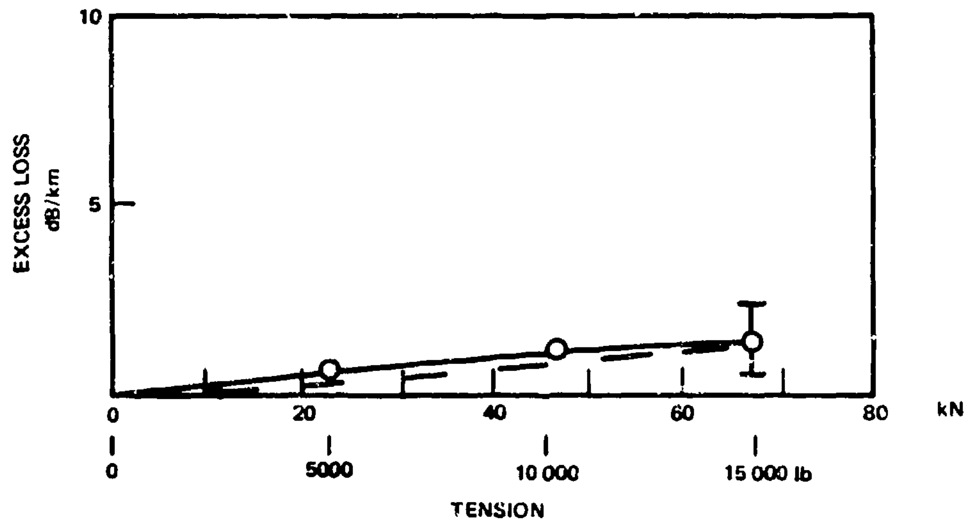

Figure 15. ITT cable tension test, fiber 3N, (step-index), cycle 4.

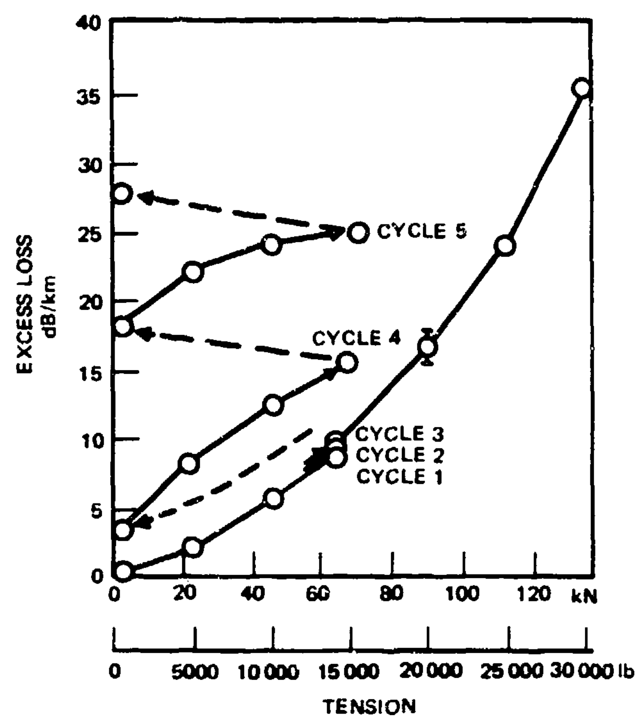

Figure 16. ITT cable tension test, fiber 5N (graded-index).

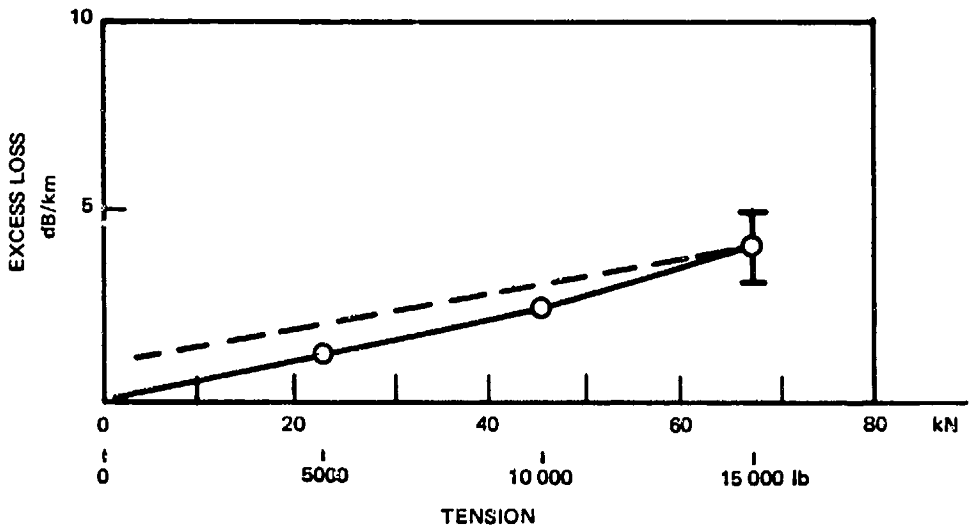

Figure 17. ITT cable tension tests, fiber 6N (step-index).

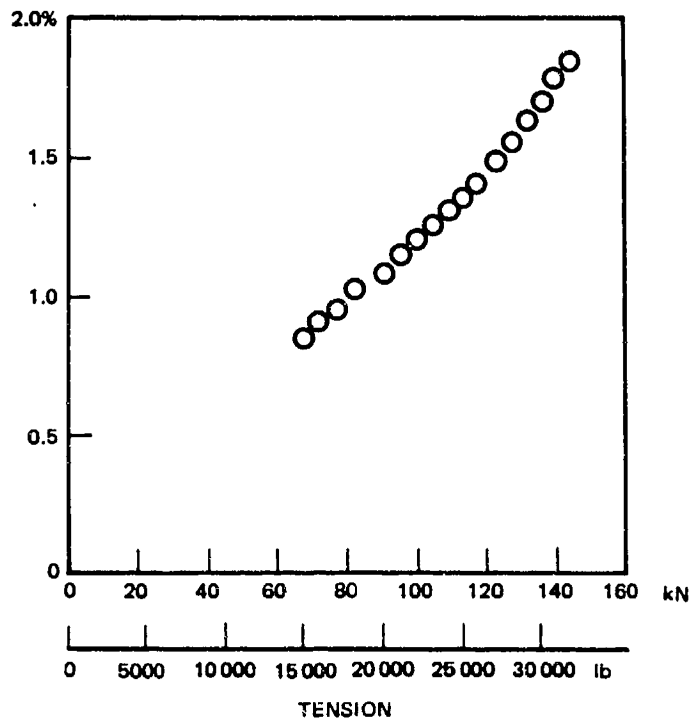

Figure 1ь. Tension-strain curve for ITT cable.

Figure 19. Tears in ITT cable following tension test.

RESULTS

The graded-index fibers in the ITT cable were strongly affected by tension. The excess loss was 10 dB/km at 67 kN (15 klbs) which is 40 percent of the specified break strength. The step-index fibers were not as strongly affected by tension (0.5 to 4 dB/km excess loss). It is likely that the excess loss was caused by microbends which are increased by tension and relieved, to some extent, by the soft "buffer" layer of plastic on the fiber.[2,3] Improvements in cable design and buffers are required to reduce the excess loss.

The Simplex cable imposed too much stress on the Corning fibers. Had these fibers not broken in the termination, they probably would have broken between 15 and 30 kN (3 to 6 klbs) when the fiber elongation exceeded 0.1 to 0.2 percent.* Because of the straight-lay configuration, it is possible to exceed 0.3-percent fiber elongation when the cable is bent around a 37-cm sheave. Small fractures in the red-colored subunit made breakage more likely; figures 20 and 21 show a section of the Simplex subunit before and during bending around a 37-cm diameter circle. These small fractures took place randomly in all samples which were dissected, approximately one per metre. These fractures may have been the source of the high excess loss in the "red" fiber and possibly contributed to the excess loss in the "black" and "white" fibers.

The step-index fibers in the ITT tow cable increased in attenuation in a manner similar to the step-index fibers in a smaller diameter sonobuoy cable developed by ITT under the same contract. The sonobuoy cable consisted of 2 stranded-steel wires and 2 optical fibers in a polyethylene jacket.[1] Figure 22 compares the increases in attenuation with normalized cable elongation.[4] The large increase in attenuation at 0.6-percent sonobuoy cable elongation was accompanied, within a few seconds, by breakage of the fiber at a small-radius termination bend. Below 0.6 percent, the curves of the step-index fibers track

*Corning estimated the fibers would probably have passed a 0.2% proof-test.

[4] Naval Electronics Laboratory Center Technical Note (in preparation), Fiber-Optic Sonobuoy Cable Environmental Tests, by DH Stephens

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Figure 20. Small fractures in Simplex subunit.

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Figure 21. Broken "red" portion of Simplex subunit.

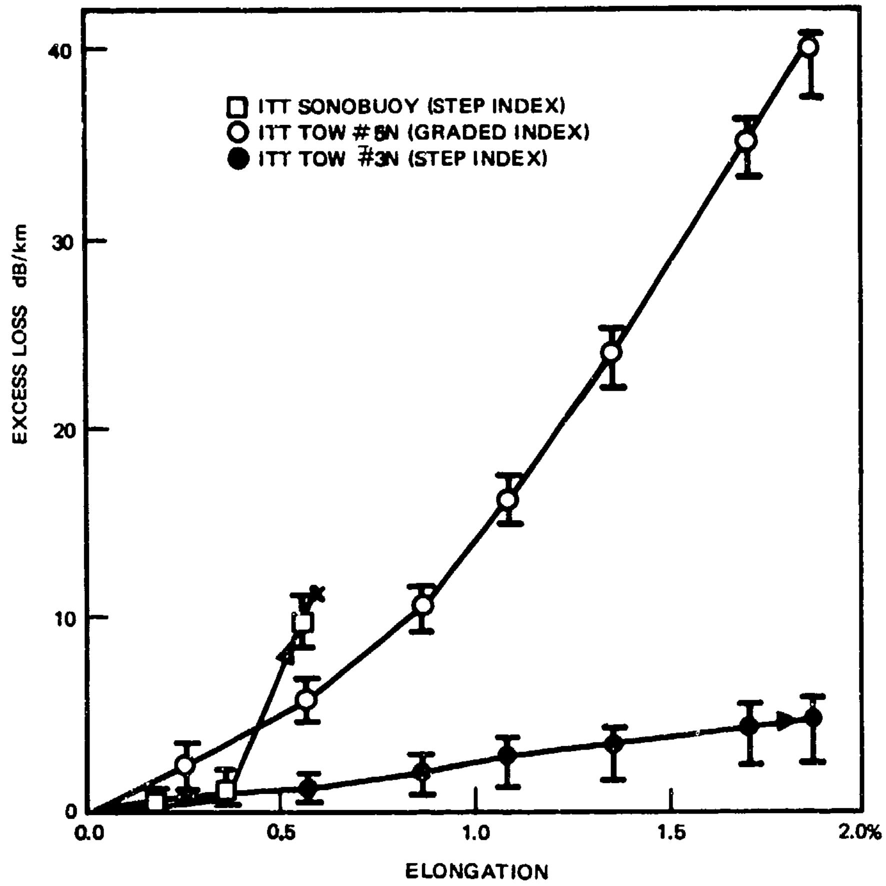

Figure 22. Attenuation versus cable elongation for ITT tow and sonobuoy cables.

closely. For both the tow and sonobuoy cables, it is apparent that further fiber protection is required to relieve stress-induced microbend losses.

ENVIRONMENTAL TESTS

TEMPERATURE CYCLING

It was planned that tests would be conducted at 65°C which represents the highest temperature at which the cable would be stored. This temperature would occur with high ambient air temperatures and exposure to direct sunlight. The plan was changed so as to test the cable between temperature extremes of +75° and −62°C as specified for a similar undersea cable.

EQUIPMENT

The temperature tests were performed by NELC using the facilities available in the Technical and Environmental Evaluation Division. Both the ITT and Simplex cables were tested in a Conrad Model FD-32-3-3 temperature/humidity chamber. The operating range of the chamber was −75° to +120°C with a temperature-control tolerance of ±1°C. In addition, during the pressure test of the ITT cable, the attenuation was monitored as the

water temperature was decreased from 18° to 1°C. Changes in optical attenuation were monitored during both tests.

PROCEDURE

The temperature-cycling test for the ITT cable was performed on a 60-metre length of cable placed in the temperature-humidity chamber. During the pressure test, the length was 167 metres. The data from the pressure test were more precise because of the increased length of cable and the increased stability of the optical measuring devices. The length of the Simplex cable was only 30 metres because of the difficulty in transmitting a usable signal through a longer sample.

Tests in the temperature chamber were conducted with the cables coiled into 1-metre diameter circles. A thermocouple was taped to the steel armor so that the cable temperature could be monitored. One metre of armor was stripped from each end of the cable sample and the cable was connected to the optical monitoring device located adjacent to the chamber. The test of the ITT cable in the pressure tank was performed with the cable formed into a 1-by-3 metre "figure-eight" configuration. The temperature cycles for each cable are shown in figures 23 and 24.

DATA

The data for each cable, expressed in dB/km of excess loss are presented in figures 25 and 26. Much higher losses were measured in the temperature-chamber test than in the pressure-tank test of the ITT cable; at 1°C, the excess loss was measured to be 5dB/km in the chamber and 1.6 dB/km in the tank for fiber 5N (graded-index). For fiber 3N (step-index), the increase at 1°C was equal to the instrument precision (0.3 dB/km) for the measurement in the pressure tank. The difference in measured values is larger than the measurement precisions. A possible explanation is that most of the power which is injected at higher launch angles is radiated in the first 50 metres, indicating an attenuation which is larger than would be measured in longer lengths. This phenomenon has been observed in backscatter experiments.[5]

The Simplex cable attenuation increased 50 dB/km at 1°C before cooling to −62°C and over 100 dB/km at 1°C after cooling.

TEMPERATURE CYCLING RESULTS

The step-index fiber, 3N, in the ITT tow cable, was not affected by cold temperature. The excess loss was 0.3 dB/km which was within the instrumental precision of 0.3 dB/km. The graded-index fiber, 5N, excess loss was 1.6 dB/km; a significant part of the loss budget for systems which, for example, require 6 dB/km total attenuation limits.

The Simplex cable was found to be very sensitive to low temperatures; its attenuation increased 50 to 100 dB/km at 1°C. This increase is suspected to be the results of (a) stress caused by armor contraction, (b) rough surfaces near the fiber, and (c) poor buffering. The temperature effects are much smaller in cables which have no armor (such as sonobuoy cables); the Air Logistics sonobuoy cable,[4] which is an ITT fiber (PFA buffer) ruggedized in an S-glass sheath, showed very little excess loss at −4°C (approximately

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[5] Barnoski, MK, et al, "Fiber Waveguides: A Novel Technique for Investigating Attenuation Characteristics," Applied Optics, v 15, no 9, September 1976

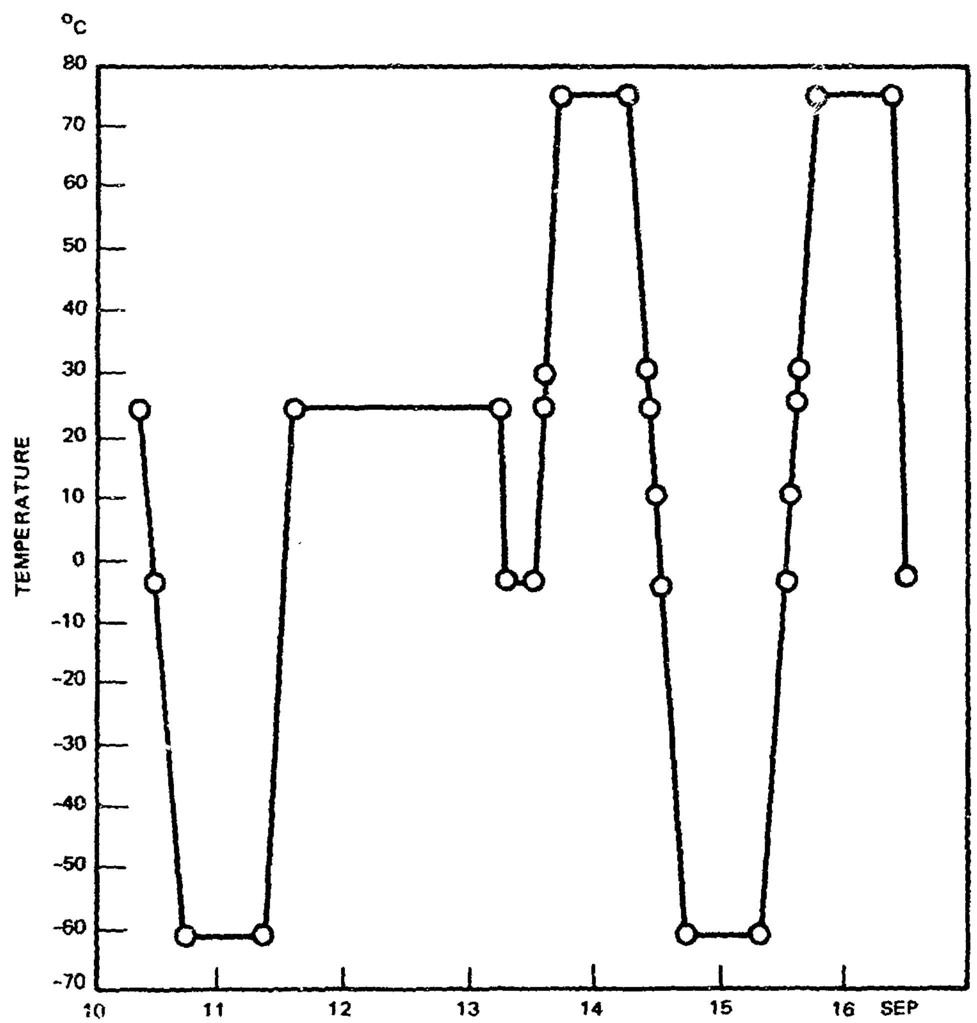


Figure 23. Temperature cycle for ITT cable.

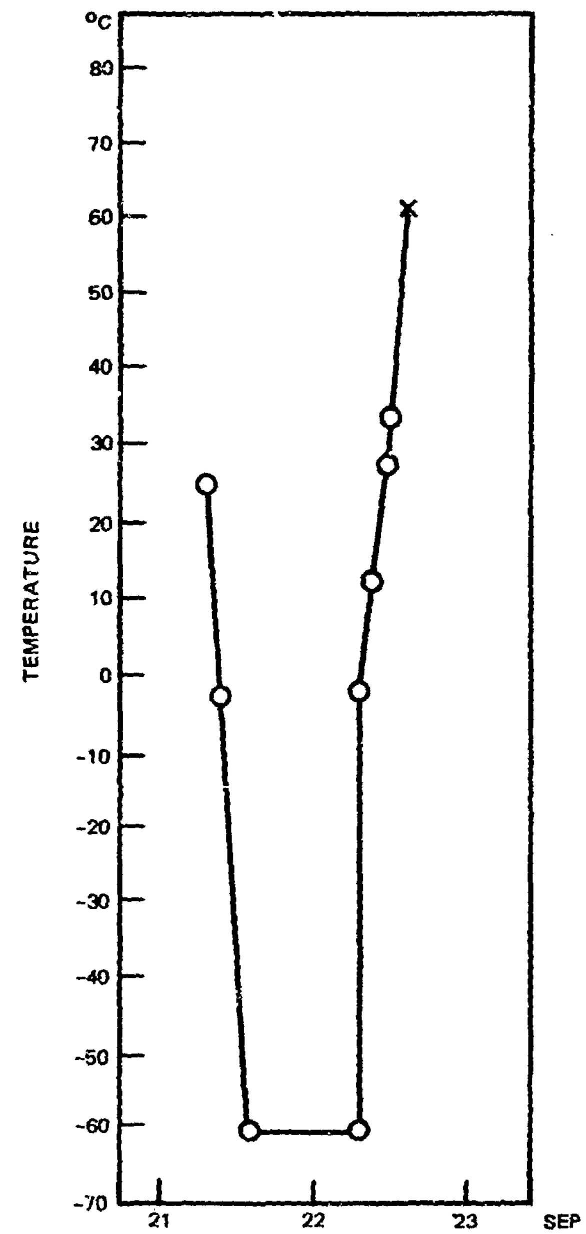


Figure 24. Temperature cycle for Simplex cable.

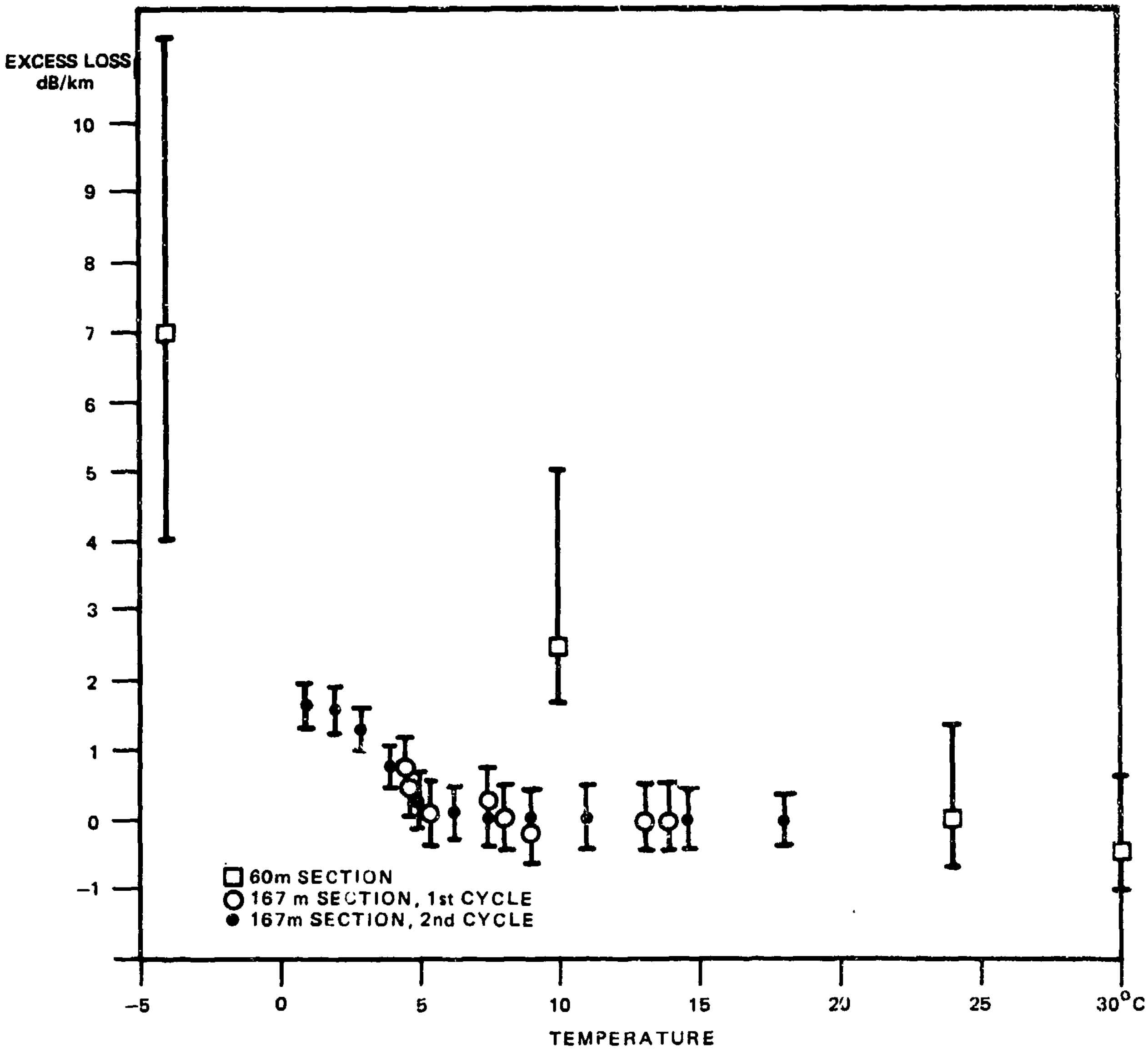


Figure 25. Temperature test, ITT fiber 5N (graded-index).

0.7 dB/km) (see figure 27). The Simplex tow cable, which contained 3, Corning, Kynar-coated, Air Logistics-buffered fibers in S-glass sheaths, was in a highly stressed state because the three sheaths were epoxied together to form a straight-laid 3-mm diameter rod. When the rod was bent, the rough-surfaced Kynar coating was forced against the walls of the S-glass sheaths, causing attenuation increases.

The ITT cable may have had stresses in the optical subunit caused by the nylon filler rods and copper-wire serve around the urethane jacket. These stresses may have been greater prior to the application of the first polyethylene extrusion; in table 4, the average

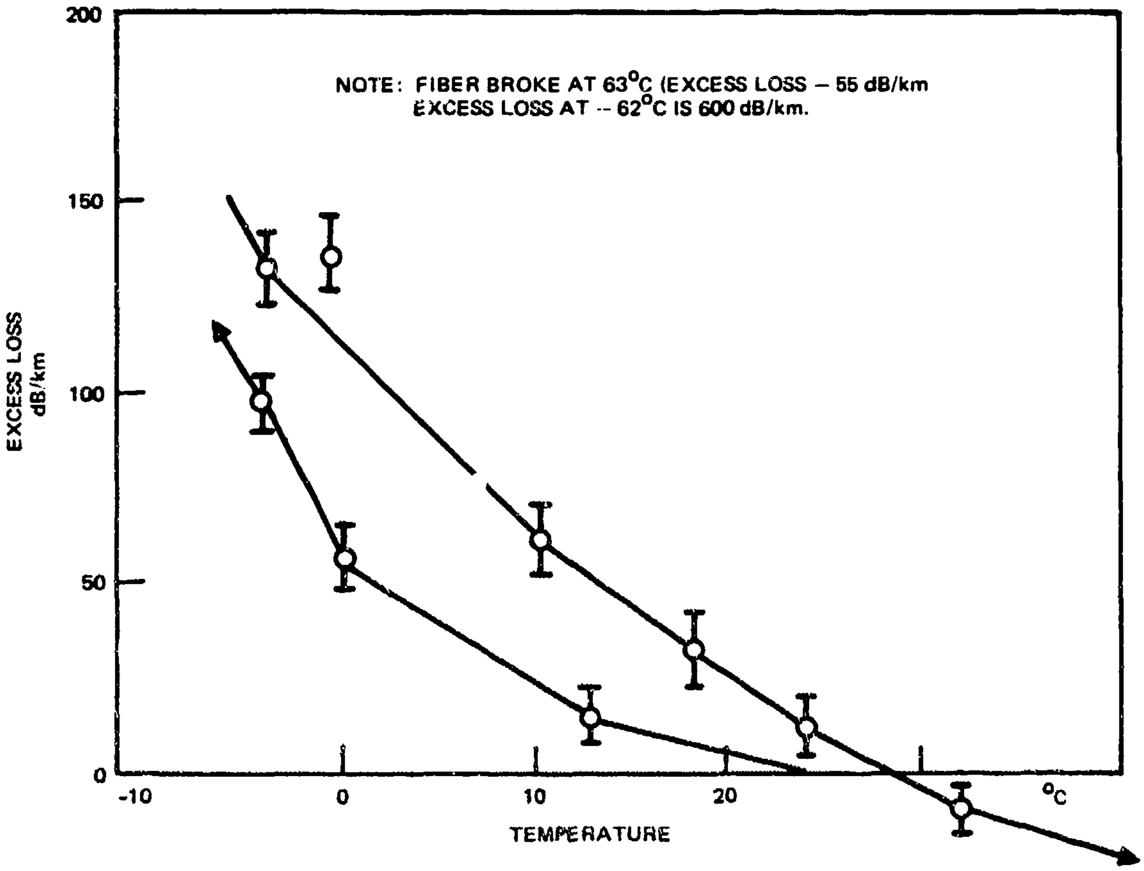


Figure 26. Temperature test, Simplex black fiber (step-index).

attenuation was lower "after dielectric." In a test it was determined that the fibers form grooves (relieving stress) in the central rod at temperatures above 90°C (such as occur during extrusions). This same phenomenon, which reduced excess loss during manufacture, may be responsible for the increased attenuation at low temperatures; the central rod may become less pliant, requiring the fiber buffers to absorb more of the stress imposed upon the cable. In addition, the fiber buffers may not be as pliant at low temperatures.

DIMENSIONAL STABILITY AT ELEVATED TEMPERATURE

The cables were coiled into circles 1 metre in diameter during the temperature tests. In addition, a smaller loop was formed in a short sample of each cable. This smaller loop was flexed at high temperature to determine if the fibers moved from their initial positions. Integrity of the fiber configuration is critical to the survival of the fibers.

The epoxy employed in the Simplex tow cable is incapable of holding S-glass together at temperatures above 63°C, which is far below the specified 75°C. The ITT cable was not affected by high temperatures (75°C) other than some oozing of the polyethylene grease from the cable ends.

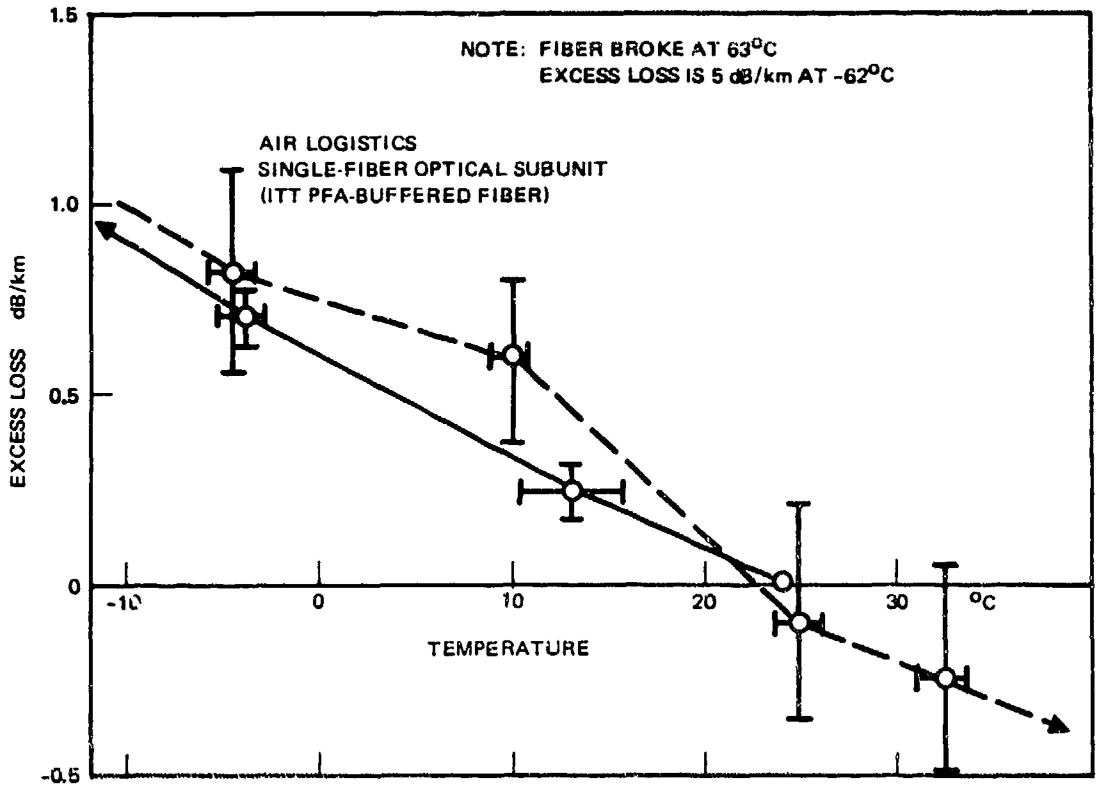


Figure 27. Temperature test, Air Logistics sonobuoy cable (similar to Simplex optical subunit).

THERMAL SHOCK AND COLD BEND

Short samples of each cable were heated to 75°C and then placed in ice water to determine if shrinkage of the buffer material or other cable components might damage the fibers. Samples of each cable were also cooled to -62°C and flexed in circles 37-cm in diameter.

Both cables apparently were not harmed by cold temperatures. They were as flexible at 62°C as at room temperature and no damage resulted when the cables were bent to 37-cm diameter circles. The Simplex cable did not pass the thermal shock test because it failed to transmit light as it was heated above 63°C. The ITT cable passed; all fibers transmitted light after the test.

HOSING

Both cables were specified to be nonhosing design. It was planned to conduct the high-pressure tests with one end of the cable open inside the chamber and the other

protruding from the pressure vessel. This test was not performed because a sufficiently safe seal could not be formed around the cable. Instead, MIL-C-951E (Hosing) was performed at ITT on the ITT cable. The ITT cable was water-blocked, except in the optical subunit. Water was observed leaking through the optical subunit, but the amount was less than the MIL-C-951E specification.

PRESSURE TESTS

Although tests of buffered fibers at Corning Glass Works, under NELC contract N00123-75-1023, had revealed no attenuation increase at pressures up to 140 MPa (20 kpsi),[4] tests were planned on the tow cables to determine if nonuniform forces were exerted on the fibers by the other cable component. The cables were tested in fresh water; saltwater was not available at the test facility during the testing period.

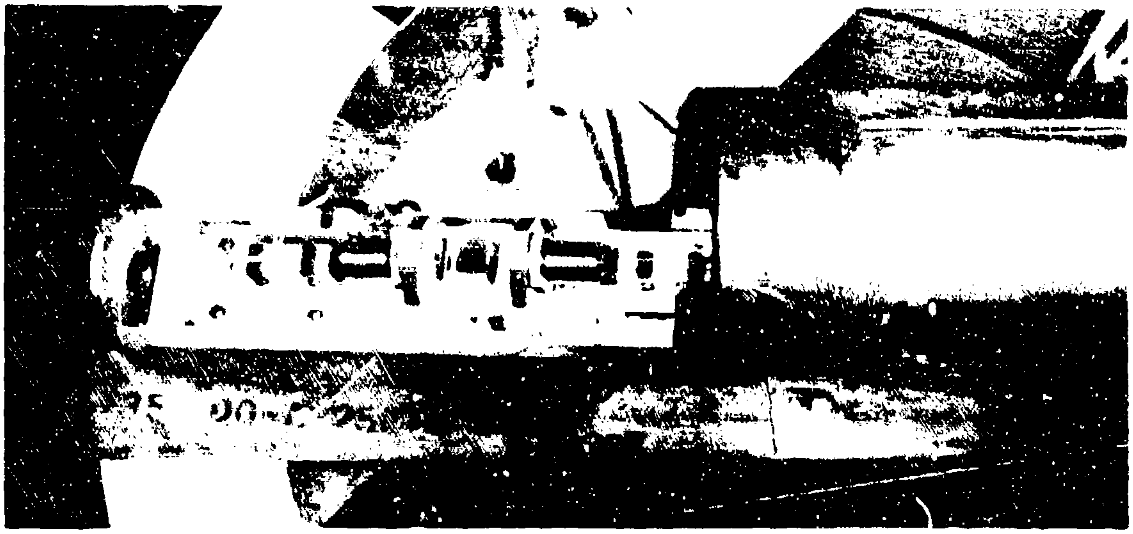
EQUIPMENT

The pressure test was repeatedly delayed and was finally redesigned because of optical and mechanical equipment problems. Figure 28 shows the optical device as originally configured. The small pressure cylinder contained the optics, source, and detector. Optical and electrical crosstalk was too large, compared to the relatively small signal changes, and the pressure test was redesigned. The optical monitoring device was removed from the pressure chamber and the detector-to-amplifier distance was shortened to 1 metre. The detector was operated unbiased as a photovoltaic device.

Both ends of the fiber were epoxied into an NELC-developed feedthrough, figure 29, leaving 2 metres of fiber for the monitoring devices. The ferrule containing the fibers was sealed against the inner flange of the pressure vessel using an O-ring. No suitable adhesive could be found which would prevent water from leaking around the ITT fiber buffer. The buffer is PFA which is similar to TFE teflon in several respects. Teflons are sealed by etching the surface with a sodium-naphthalene dispersion prior to the application of the adhesive; the etch had no effect upon the PFA buffer. Several tests were attempted using commercial adhesives, all of which ended with the fibers extruding through the feedthrough.

A different approach had been taken with earlier tests on sonobuoy cables.[4] This feedthrough used a neoprene gland which was tightened around the fiber with a threaded nut (figure 30). Pressure-dependent attenuation was introduced by the neoprene gland and this approach was abandoned.

The feedthrough problem was eventually solved by removing the fiber buffer from a 3-mm length of cable within the ferrule. A filled epoxy (Marine Tex) was then placed around the exposed fiber to form a solid adhesive bond between the glass and the metal.



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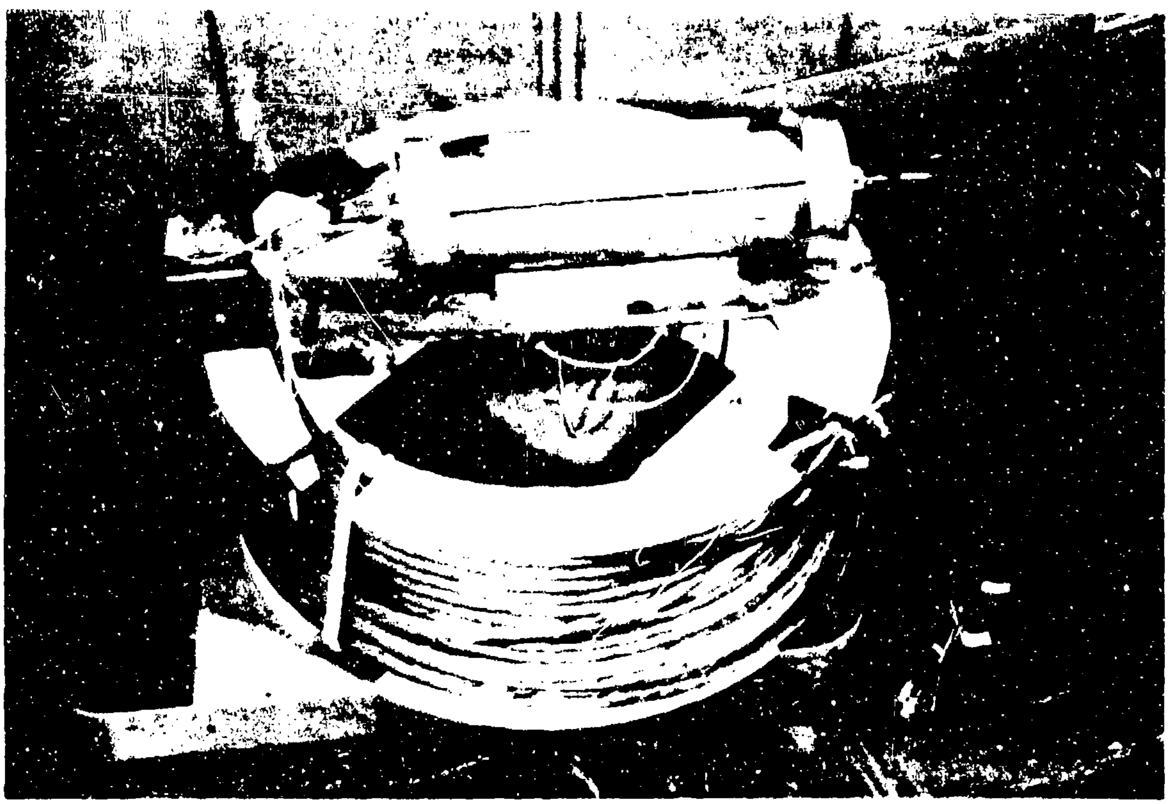
A. Optical monitoring device.



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B. Pressure housing and cable.

Figure 28. Original configuration of optical monitoring device.

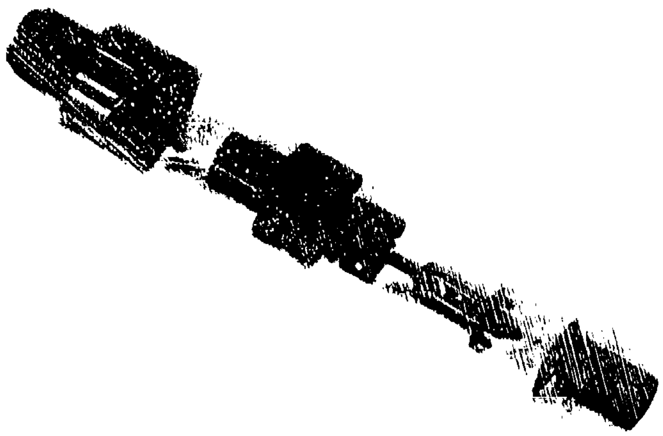

Figure 29. NELC high-pressure fitting with an epoxy (Marine Tex) sealant.

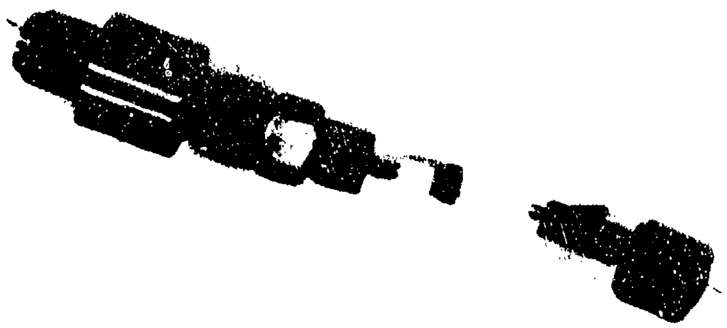

Figure 30. CONAX MTG series high-pressure fitting with a neoprene sealant.

The seal was effective in preventing leaks without adding attenuation at pressures up to 69 MPa (10 kpsi). Extreme care was needed when the epoxy seal was formed; the ITT cable fibers broke 9 times before a successful seal was obtained in the feedthrough.

For the ITT cable test, the equipment was operated adjacent to the pressure chamber (figure 31) and observed from behind a safety screen. The safety screen, a steel plate, 6 mm thick, is required in all pressure tests because of the possibility of a failure of the seal at high pressure.

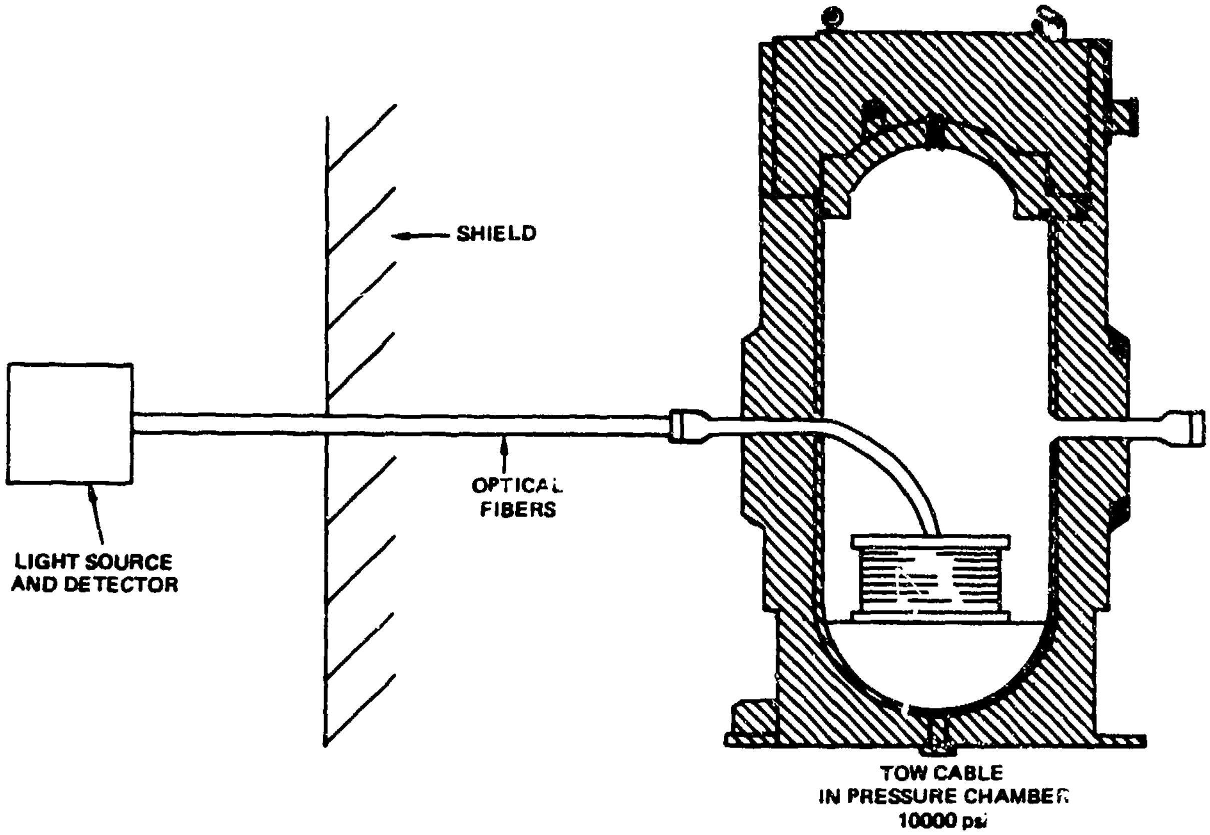

Figure 31. Pressure test fixtures.

PROCEDURE FOR PRESSURE TEST

The cable sample was lowered into the pressure chamber and connected to the optical monitoring device via the fiber pressure feedthrough. The chamber was then filled with water. The water for the ITT cable test was chilled to 4°C prior to the start of the test (during the first cycle, the water cooled to 1°C and remained at that point for the second cycle). The step-index fiber, 3N, and the graded-index fiber, 5N, of the ITT cable were selected for monitoring. On the Simplex cable, the "black" fiber (step-index) was the only fiber through which a usable signal could be obtained. The Simplex cable was not tested at low temperatures because of the lack of time available for cooling [had cooling been attempted, the test would have required an extra day–higher-priority tests were scheduled immediately following completion of the abbreviated test].

The attenuation was monitored at 6.9-MPa (1000-psi) intervals up to 69 MPa (10 000 psi). Operating at 20 strokes per minute, the hydraulic pressure ram took approximately 10 minutes between each reading. Pressure could be relieved at less than 1 minute per reading. During the long pumping time, some instrumental drift was encountered in the Simplex test; error bars indicated the probable limits on the drift (the drift problem was solved prior to the ITT cable test).

DATA

The curves of attenuation versus pressure for the ITT and Simplex tow cables are presented in figures 32 and 33. For the ITT cable, the attenuation increase at 69 MPa was measured to be 0.4 dB/km (0.2 dB/km precision) for the graded index fiber and 0.0 dB/km (0.3 dB/km precision) for the step index. The attenuation of the feedthrough was found to be 0.03 dB for the graded-index fiber and 0.07 dB for the step-index. The Simplex cable had a factor of 50 higher excess loss (note change in scale). Within a few minutes of reaching maximum pressure, the fiber broke within the cable. Maximum attenuation was 176 dB/km.

RESULTS

The ITT cable was less sensitive to pressure than to changes in temperature or tension. The attenuation increase took place at pressures above 40 MPa (6 kpsi), indicating that the excess loss is experienced only in those portions of cable exposed to depths greater than 4 km (13 000 feet). The higher attenuation readings on the decreasing portions of the curves may have been because of the rapid (8-min) depressurization.

The Simplex cable attenuation increased immediately with pressure, rising to 58 dB/km at 6.9 MPa (1 kpsi) and to 128 dB/km at 13.8 MPa (2 kpsi). With increasing pressure, the cable attenuation decreased slightly until it again climbed sharply at 62 MPa (9 kpsi). The high attenuation is believed to result from microscopic voids within the S-glass optical subunit. During manufacture of the cable, Simplex encountered considerable difficulty extruding a polyethylene layer over the subunit because of outgassing. The high attenuation of the cable (120 dB/km for the best fiber) indicates a severe microbend problem which is made worse at high pressures.

This problem was also observed in the Air Logistics sonobuoy cable which had an S-glass sheath similar to the Simplex tow cable optical subunit (figure 34). At 34.4 MPa (5 kpsi), water drops were observed at one end of the cable indicating a flaw in the strength member.

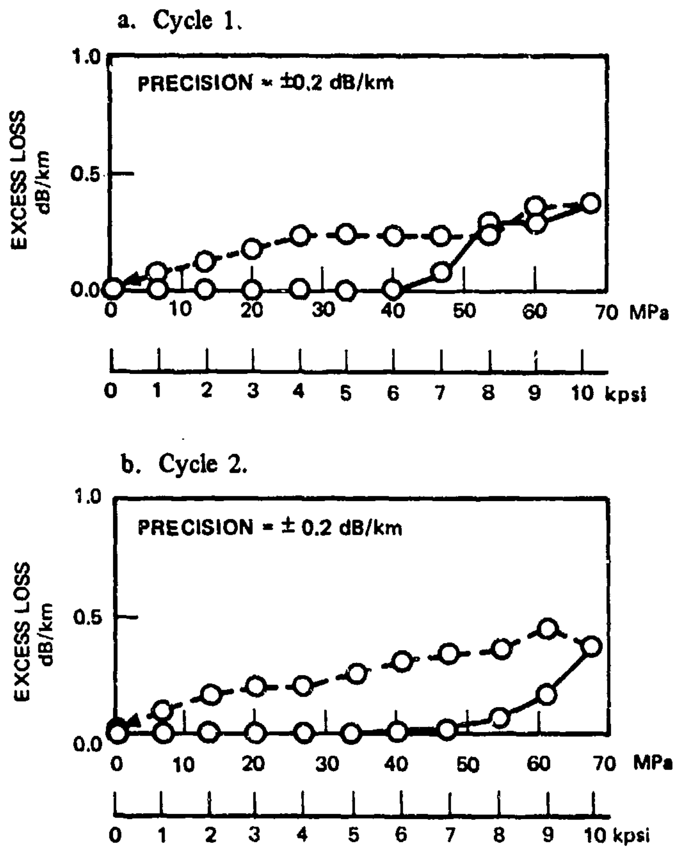

Figure 32. ITT cable pressure tests, graded index fiber.

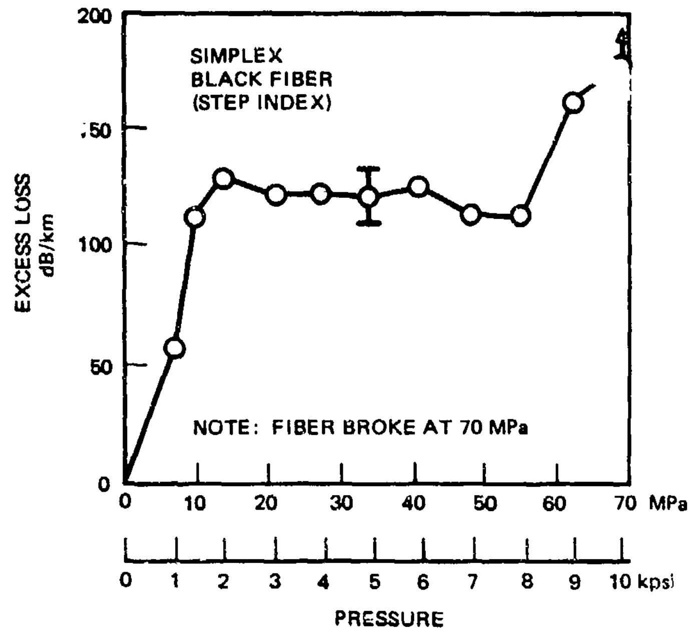

Figure 33. Simplex cable pressure test.

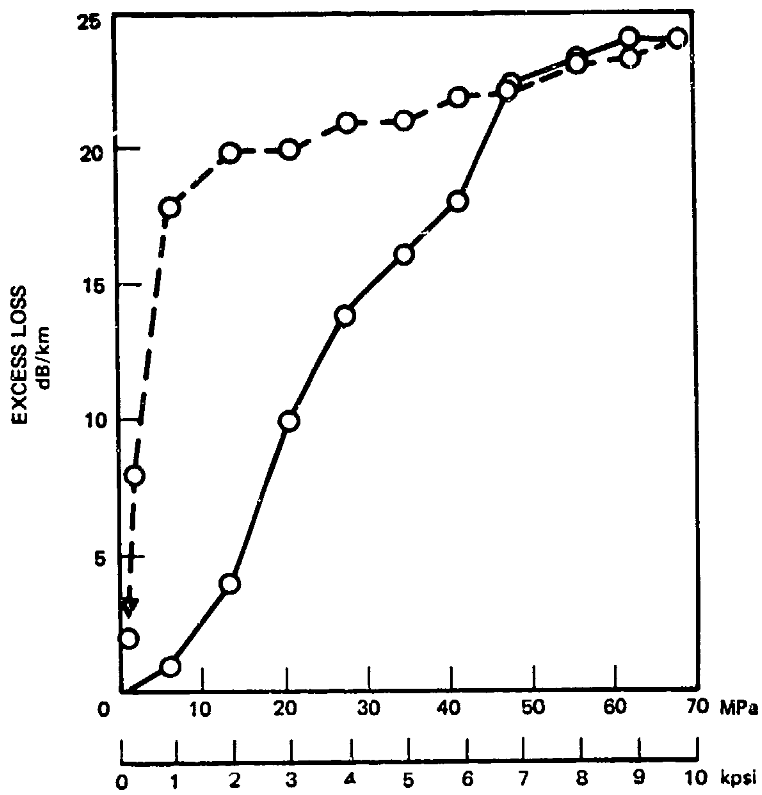

Figure 34. Air Logistics Sonobuoy cable pressure test.

SUMMARY OF RESULTS

A summary of the optical, mechanical, and environmental test results is presented in table 7.

TABLE 7. SUMMARY OF TEST RESULTS

OPTICAL	ITT CABLE (6 fiber)						SIMPLEX CABLE (3 fiber)		
Spectral attenuation, dB/km									
At 820 nm	6	9	7	14	6	8	120	450	570[a]
At 1050 nm	3	5	4	14	5	5	130	550	
Numerical aperture	0.23	0.24	0.25	0.15	0.16	0.19	0.19[b]	0.19[b]	0.19[b]
Dispersion, ns/km	54	50	50	2	2	40	30[c]	36[c]	40[c]
Optical isolation	>83 dB						(d)		
MECHANICAL									
Excess loss for tension to 67 kN (15 klbs), dB/km	0.5	2	2	10[e]	(f)	4	(g)		
ENVIRONMENTAL									
Excess loss for 32°C, dB/km	-1 (graded)[h]						-10[i]		
Excess loss for 1°C, dB/km	0 (step), 1.5 (graded)[h]						50[i]		
Dimensional stability at 75°C	pass						fiber broke (63°C)		
Thermal shock	pass						fiber broke (63°C)		
Cold bend	pass						pass		
Hosing	pass						(j)		
Excess loss, dB/km, for pressure									
At 48 MPa (7 kpsi)	0 (step), 0 (graded)[k]						130[l]		
At 69 Mpa (10 kpsi)	0 (step), 0.4 (graded)[k]						176[l]		

a. Measured with HeNe laser at 633 nm.

b. The high attenuation left insufficient signal for an NA measurement. Corning measured 0.186 prior to cabling.

c. Dispersion not measured because of high attenuation. Data in table were measured at NELC prior to cabling.

d. High attenuation in the cable prevented the performance of this measurement; there was not transmission over the full cable and, in a short section (94 m), the light through the "red" fiber, for example, was near the instrument sensitivity, leaving no dynamic range in which to measure light in adjacent fibers.

e. Excess loss for first 3 cycles was 10 dB/km. After the fourth cycle, fiber apparently broke.

f. Fiber apparently broke before the fourth cycle.

g. All fibers broke prior to test. Fibers were broken in termination (small-radius bend) and within cable (possibly at the 37-cm diameter sheave wheel).

h. Negative excess loss indicates increased transmission. The step-index fiber, 3N, and the graded-index fiber, 5N, were tested.

i. The step-index fiber, "black," was selected for measurement. Upon return from -62°C, the excess loss was 135 dB/km.

j. ITT tested the cable to MIL-C-915E and the cable passed the 25-psi test.

k. The step-index fiber, 3N, and the graded-index fiber, 5N, were tested.

l. The "black" fiber was selected for measurement. After 4 attempts to seal the fiber, 30 m (of the original 60 m) was successfully tested. When the maximum pressure was reached, the fiber broke.

CONCLUSIONS

The test results of these cables, which were the first two fiber-coptic cables developed for undersea applications, established the feasibility of using fiber optics in undersea tow cables. The following conclusions are drawn from the specific test results of each cable:

ITT CABLE

1. Optical fibers can be cabled with very little excess loss during manufacture: two step-index fibers and one graded-index fiber had less than 6 dB/km attenuation at 0.85 μm; all four step-index and the same graded-index fiber had less than 5.5 dB/km attenuation at 1.05 μm. These attenuations were significantly below the contract-specified 15 dB/km attenuation.*

2. Wide-bandwidth/length products are achievable with cabled optical fibers; both graded-index fibers had dispersions of less than 1 ns over the 520 m length. The contract specification was 5 ns.* The measured 20-27 ns dispersions (520 m length) of the four step-index fibers were consistent with theoretical estimates based on measured numerical apertures (there was no contract specification for step-index fiber dispersion). The lack of precision on short (0.5 km) cables and the nonlinear relationship between dispersion and length prevent extrapolation of dispersion results to multikilometre cables.

3. Measurements of the step-index fiber, 3N, indicate that the step-index fibers are not affected (0.3 dB/km precision) by either cold temperature (1°C) or high pressure (69 MPa or 10 kpsi).

4. Measurements of the four step-index fibers indicate that tension to 67 kN (15 klbs) increased attenuation 0.5 to 4 dB/km.

5. Measurement of the graded-index fiber, 5N, indicates that graded-index fibers are not affected (0.2 dB/km precision) by temperature in the 5°C to 25°C range or pressure in the 0 to 48 MPa (7 kpsi) range. The combined attenuation increase at 1°C and 69 MPa was 1.9 dB/km.

6. Measurement of the graded-index fiber, 5N, indicates that tension seriously affects graded-index fibers: at 67 kN attenuation increased 10 dB/km.

7. If the optical fibers are to survi.e tensile loads associated with the maximum cable elongation, they must have minimum elongations-to-break which exceed 2.5%. If the deficient polyethylene cable jacket is replaced with one which prevents collapse of the surrounding armor wires under tension, the fiber elongation is calculated to be 1.2%. The fibers were proof-tested to 1% at ITT prior to cabling. During load cycling of a 50-m section, two of the six cabled fibers (both graded-index) broke at elongations of 0.8% after a 30-minute loading to 1.85%. (Preliminary results of the mechanical tests at TMT indicate no difference in strength between the cabled step- and graded-index fibers.)

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*The 15 dB/km attenuation and 5 ns dispersion contract specifications were selected to represent readily available fibers (1974) in order to minimize development costs

SIMPLEX CABLE

1. The cable had very high cabling losses; the 5-dB/km (before cabling) attenuation of the fibers was 120 to 570 dB/km after cabling. This cable was also strongly affected by temperature and pressure. Under conditions similar to those of the ITT cable tests, the Simplex cable attenuation increased 50 to 130 dB/km with temperature and 176 dB/km with pressure. During both tests, the optical fiber broke (at 63°C and 69 MPa).

2. The attenuation increases in the Simplex cable are believed to result from microbends[2,3] associated with (a) the rough-surfaced Kynar coating on the fibers which formed lumps in the Air Logistics buffer surrounding the coating, (b) the straight-lay design of the 3-fiber optical subunit which increased bending strain on the fibers, and (c) fractures (one per metre) in s-glass of the optical subunit which were points of stress concentration.

RECOMMENDATIONS

1. Develop a follow-on cable using the experience gained in the development of the first cables and recent improvements in:

   a. fiber attenuation, dispersion, numerical aperture, and strength, and

   b. cable design, buffering techniques, and cabling machinery.

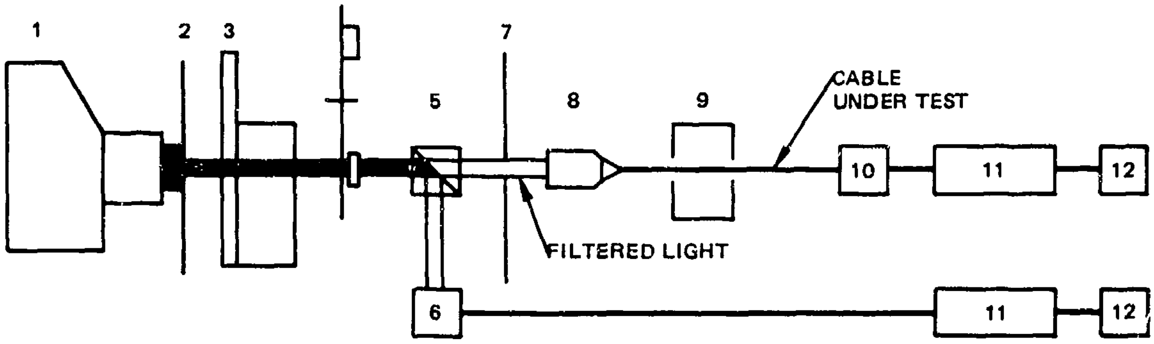
These factors are expected to significantly reduce or remove all noted cable deficiencies.

2. Continue the fiber strength and fatigue improvement program supported by DARPA.

APPENDIX A: EQUIPMENT

SPECTRAL ATTENUATION

Spectral attenuation equipment, similar to that in operation at Corning Class Works and ITT, was assembled at NELC for undersea cable attenuation measurements (figure A1).



1. 200 W mercury vapor short-arc lamp.
2. 1.0 mm aperture, imaged with 35:1 reduction ratio into 30 μm fiber core.
3. Light Chopper, PAR Model 125, frequency 540 Hz. Also provides electrical sync for lock-in amplifiers.
4. Filter wheel. 11 filters from 500 nm to 1050 nm.
5. Beam splitter.
6. Reference detector, 10 mm diameter silicon PIN, monitors lamp output.
7. Numerical aperture slide. 10 apertures equivalent to 0.02-0.24 NA.
8. 16 mm, 10X, 0.25 NA flat-field objective images 1 mm aperture onto fiber.
9. Fiber in V-groove holder with XYZ positioner.
10. Signal detector, 2 mm silicon PIN, measures light through cable.
11. Lock-in amplifiers, PAR HR-8 with Type A preamps, for signal and reference detectors.
12. Digital voltmeter.

Figure A1. Spectral attenuation equipment.

Light from the arc lamp (1) is injected into the fiber (9) at 11 different wavelengths. The power through the tow cable is measured (10, 11, 12) and is normalized to the reference detector output (6, 11, 12). The fiber is then cut 1 metre from (9) and the light through this short section is measured, normalized to the reference detector. The attenuation, in dB/km, is then:

$$\frac{1}{\text{length}} \times 10 \log (V_{short}/V_{long})$$

Precision is approximately 0.2 dB; or 0.5 dB/km for the ITT cable and 2 dB/km for the Simplex cable. Accuracy of the spectral-attenuation measurements depends upon a number of factors, including fiber alignment and fiber-end preparation. The 0.5 dB/km assumes perfect alignment and that the fiber end has been prepared 3 times to remove random errors. To achieve the lowest error requires extreme operator patience: average time for the 6 ITT fibers (excluding 3 hours for cable stripping and time spent repairing equipment) was 3 hours per fiber. As an overall check, one of the ITT fibers was measured twice: the average difference between the first and second sets of 11 measurements was 0.4 dB/km with a standard deviation of 0.2 dB/km.

FIBER END PREPARATION

Both cables were mechanically stripped at the ends to expose 1 metre of fiber. ITT fibers were taped to the table with masking tape. The fiber was held at the end and a cut was made toward the end. The first cut was on top, 8 cm from the end and was 3 cm long. The second cut was on the bottom 8.1 cm from end. This removed the inner buffer coating, leaving a bare fiber. The Kynar-coated Corning fiber in the Simplex cable was stripped using acetone. The fiber was then placed in tension over a 4-cm radius and scribed with a diamond stylus. The broken end was inspected for surface smoothness with a 200-power microscope.

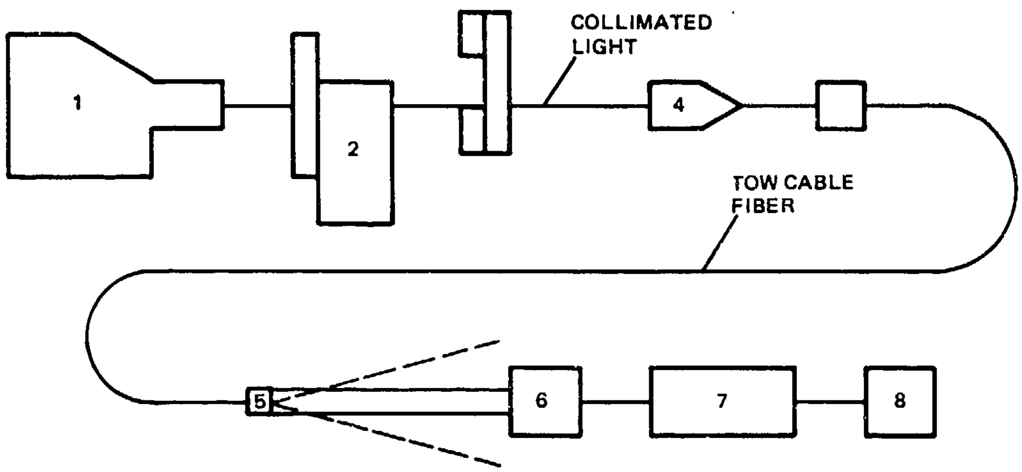
The lamp must be excited prior to powering the lock-in amplifiers or their preamplifiers may be damaged. The image of the 1-mm aperture was focused onto the core of the fiber with the filter removed. Light through the fiber was then peaked by observing the signal output and adjusting the XYZ positioner.

Data were taken at 11 wavelengths. The signal was peaked at each wavelength by adjusting the XYZ positioner. The end of the fiber was then prepared a second time. If a higher reading was obtained, the difference in dB was subtracted from each of the attenuations at 11 wavelengths. The end of the fiber was then prepared a third time as a final check. Only the highest reading was used. The consistency of readings is improved if glycerin is used for index matching between the fiber end and signal detector. The fiber was then cut 1 metre from the input end and the process was repeated, preparing the end 3 times. The short- and long-section readings were normalized to the reference detector outputs and the attenuation was computed using the previously described attenuation equation.

The Simplex cable had such high attenuation that only the "black" and "white" fibers could be measured using the spectral attenuation equipment. Instead, the arc lamp was replaced by an HeNe laser, which radiates at 633 nm.

NUMERICAL APERTURE

The spectral attenuation equipment was modified for the numerical aperture measurement, as shown in figure A2.



1. 200-W, mercury-vapor, short-arc lamp.
2. Chopper, PAR Model 125, 540 Hz.
3. 0.82-μm filter.
4. 10X objective.
5. NA table to hold detector.
6. Detector, same as signal detector for spectral attenuation.
7. Lock-in amplifier, PAR Model HR-8.
8. Digital voltmeter.

Figure A2. Numerical aperture equipment.

Light is injected at high NA into the fiber and the output is scanned using a small detector. In order to maximize the signal available, the entrance pinhole and beamsplitter (2 and 5 of figure A1) are removed. At 19-cm distance for the fiber, the detector subtends 0.7°.

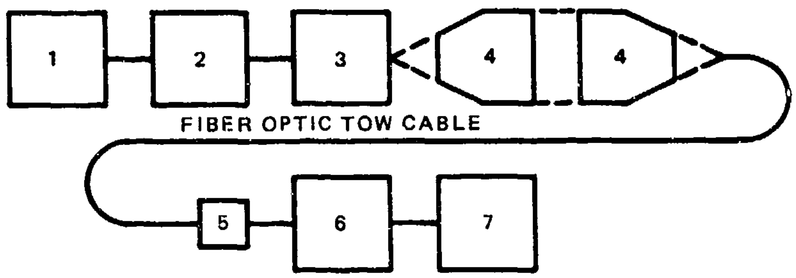
Data are taken in 1.4° increments and plotted against relative intensity. The width of the curve at 10 dB below maximum is considered to be the numerical aperture.

DISPERSION

The equipment for dispersion measurement is shown schematically in figure A3.

A narrow pulse is injected into the fiber and detected at the other end with an avalanche photodiode. The pulse is displayed on an oscilloscope and recorded on an X-Y recorder. The spread in the pulse, corrected for input pulsewidth, is the dispersion.

The fiber is aligned by placing one end near the focus of the 10X objective. An IR viewer is used to observe the light emerging from the fiber as the input is peaked. The output end is then placed near the APD detector. The pulse shape is adjusted by successive adjustments of pulse generator output, pulse amplitude, laser voltage and APD voltage until a minimal width pulse is obtained. The resulting pulse is then plotted on the X-Y recorder. Each fiber was measured both on the shipping reel and in the straight condition.

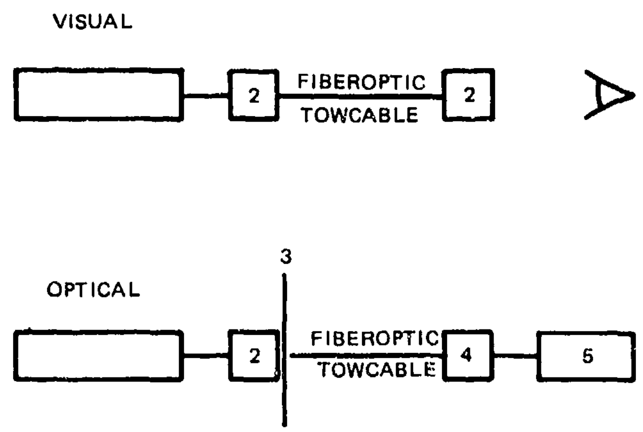


1. Pulse generator, Hewlett Packard 214A.
2. Laser driver circuit (ref 6)
3. Laser diode RCA SG2001.
4. 10X microscope objectives.
5. Avalanche photodiode, TI XL-55.
6. Sampling oscilloscope, Tektronics 561A, S-2 sampling head.
7. X-Y recorder.

Figure A3. Dispersion equipment.

OPTICAL ISOLATION

The isolation (crosstalk) between fibers in the ITT cable was measured optically and visually, using the equipment in figure A4. The Simplex cable was checked visually for near-end crosstalk, but the far-end crosstalk could not be measured because of the high attenuation.



1. Helium neon laser, 1 mW
2. Lens, 10X
3. Chopper, PAR-125
4. PIN detector
5. Lock-in amplifier

Figure A4. Optical isolation equipment.

[6] Andrews, JR, "Inexpensive Laser Diode Pulse Generator for Optical Waveguide Studies," Rev. Sci. Instrum., v 45, no 1, January 1974

Light was injected into fiber 1 and fibers 2 through 6 were observed, visually and optically, for light at the near and far ends. The light from the laser was peaked through fiber 1N. Light coupled into the fiber was measured as follows: (1) the light at the opposite end was measured using a filtered PIN diode, (2) the filtered diode was calibrated by reducing source power to allow measurement of light with and without the filter, (3) the input power was computed by interpolation of the spectral attenuation curve for fiber 1N at 0.63 μm. For this fiber, the total attenuation at 0.63 μm was -6 dB and the filter was -7.8 dB. The power measured through the fiber was -7 dB compared to 1 volt.* The sensitivity limit of the lock-in/PIN detector was -76 dB (compared to 1 volt) for 10-sec integration. The total dynamic range, thus, was:

$$-7 - (-6-7.8) - (-76) = 82.8 \text{ dB}$$

OPTICAL MONITORING DEVICES

For the environmental and tension tests, optical monitoring devices were developed. These devices were improved versions of the "spot attenuation" equipment, developed in 1975 for the undersea cable program, which incorporate a controlled-launch numerical aperture, core illumination, and greater sensitivity to small attenuation changes (achieved by nulling the reference channel against the signal channel).

Two such devices were fabricated, figure A5. The optical source is an oscillator-driven LED and the detectors are photovoltaic PIN diodes.

LIGHT-EMITTING DIODE

The driver circuit for the LED is shown in figure A6. The timer oscillates at 1200 Hz. Each pulse toggles the J-K flip-flop, yielding a 50-percent duty-cycle square wave at 600 Hz. This signal is amplified by the 6 inverters to provide 225 mA pulses for the LED. The signal is also used to electrically synchronize the lock-in amplifier. In one device, the LED chosen was a LDL-LA-63. In the other, an RCA 30012 was employed. Both are single-junction injection lasers which radiate at 820 to 850 nm. At the relatively low drive current, the lasers operate as LEDs with 1-mW outputs.

COUPLER

Light from the LED is coupled into the input fiber using an acrylic coupler, figure A7. The fiber is first epoxied into the acrylic, flush with the edge. When the epoxy has cured, micropositioners are used to maximize light transmission as the coupler is epoxied to the flat glass window of the LED. Several layers of epoxy are used to increase the strength of the joint. Shrink tubing is used to provide stress relief on the fiber.

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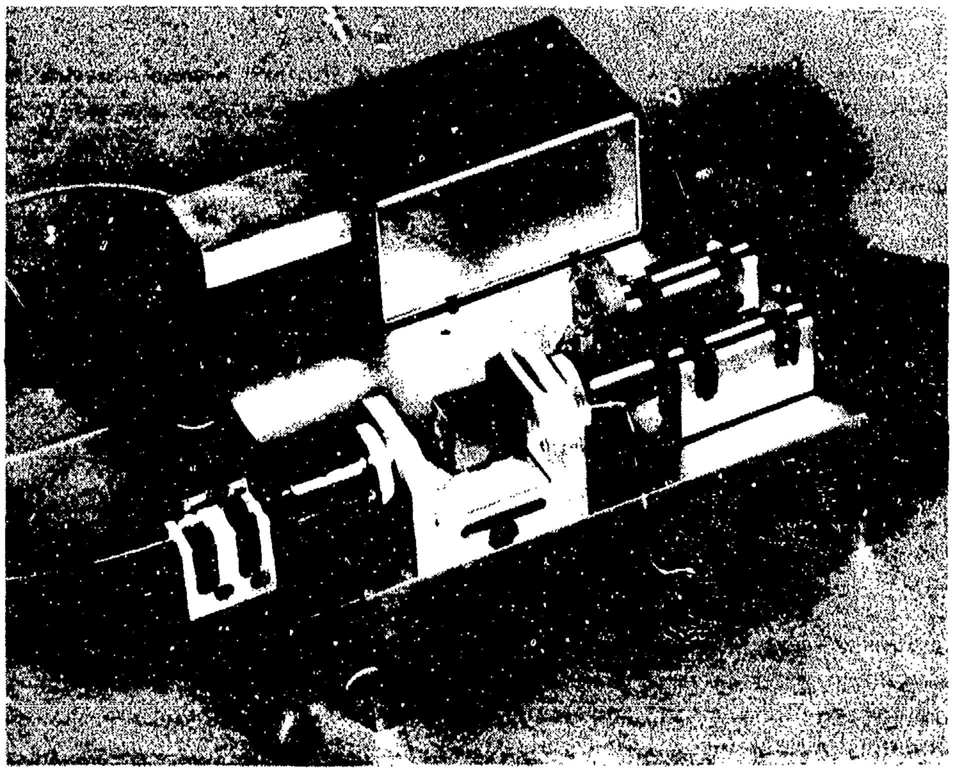
*In optical attenuation measurements, voltage (as measured at the amplifier) is directly proportional to optical power. Therefore -10 dB compared to a volt is 0.1 volt.



LSF 1033-9-76

Figure A5. Optical monitoring device for environmental and tension tests.

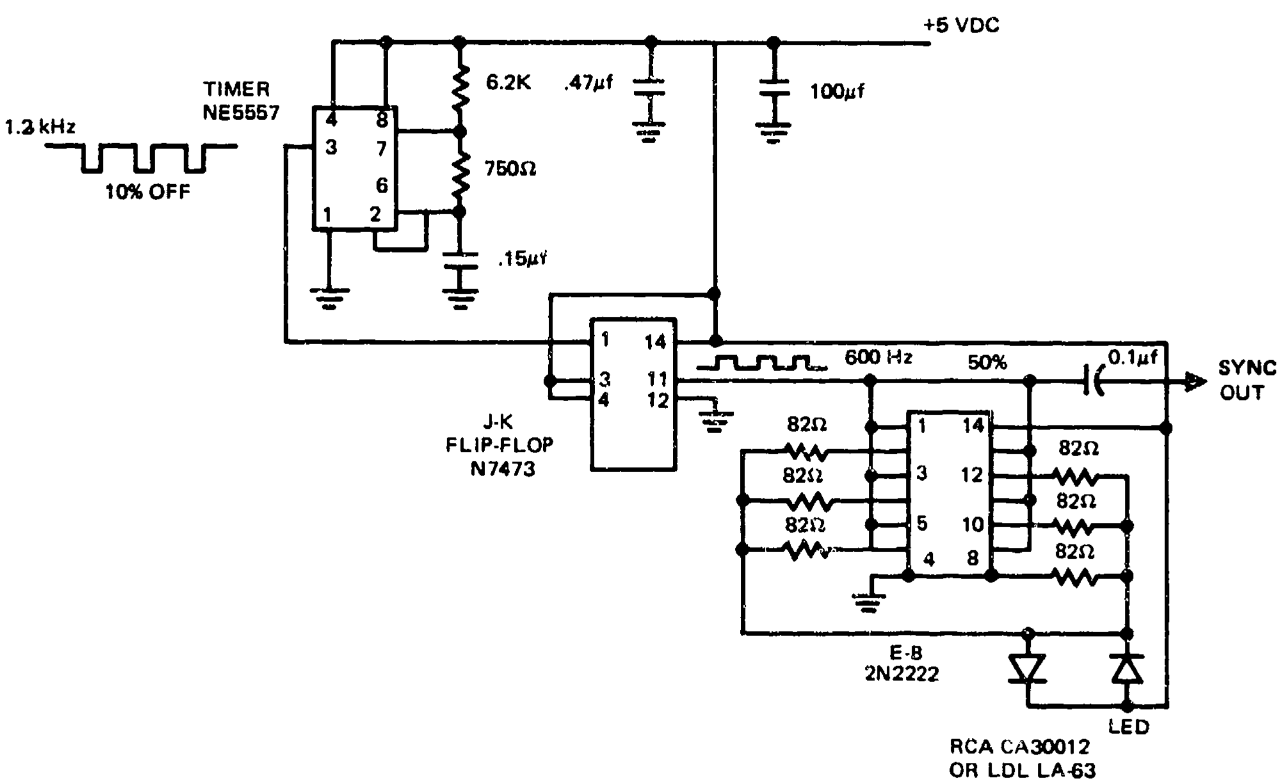


Figure A6. Driver circuit for LED.

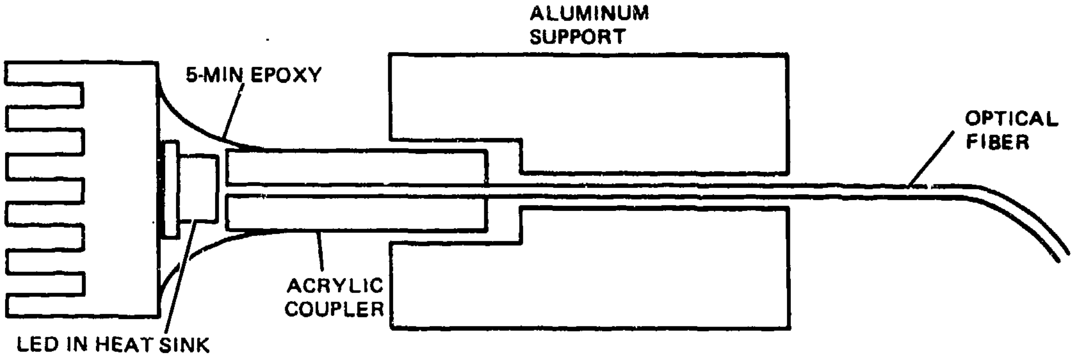


Figure A7. Acrylic LED-input fiber coupler.

INPUT FIBER

The input fiber was selected to have the following features:

(a) 0.25-NA to maximize coupling,

(b) 30-μm core to minimize light coupled into the cladding of the fiber to be tested, and

(c) silicone resin buffer to improve fiber strength so that the input fiber will not break during normal handling. The input fiber was an ITT Hytrel/silicone resin buffered CVD fiber.

OPTICS

The purpose of the optics in the devices is to provide numerical aperture control and a means of monitoring the output of the LED. Launching with the relatively small (0.1-NA) numerical aperture reduces the errors caused by differential attenuation of higher order modes. These modes, equivalent to light propagating through the fiber at angles near the limit for total internal reflection, are rapidly attenuated in fibers longer than the 50-metre lengths tested. The higher order modes, therefore, represent sources of error in short cable attenuation measurements; to the extent that the higher order modes were only partially removed by the 0.1-NA launch, the results measured represent upper bounds.

In order to increase sensitivity to small changes in attenuation, the reference detector is apertured using a small iris; the light falling on the reference detector is adjusted to equal that detected through the cable to be tested. These two signals are

subtracted electronically and the difference is amplified. Precision is approximately 0.04 dB/length of cable tested (0.2 dB/km for 200 m).

LOCK-IN AMPLIFIER

A Princeton Applied Research lock-in amplifier, model HR-8 with Type A preamplifier was used. With the RCA C30809 detectors employed, the signals measured during the tests were approximately 50 μV. The lowest usable scale is 0.1 μV on the HR-8, providing sufficient amplifier sensitivity to record attenuation changes.

APPENDIX B: REFERENCES

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2. Olshansky, R, "Distortion Losses in Cabled Optical Fibers," Applied Optics, v 14, no 1, January 1975

3. Gardner, WB, "Microbending Losses in Coated and Uncoated Optical Fibers," Optical Fiber Transmission Topical Meeting, 7 to 9 January 1975, Williamsburg, VA

4. Naval Electronics Laboratory Center Technical Note (in preparation), Fiber-Optic Sonobuoy Cable Environmental Tests, by DH Stephens

5. Barnoski, MK, et al, "Fiber Waveguides: A Novel Technique for Investigating Attenuation Characteristics," Applied Optics, v 15, no 9, September 1976

6. Andrews, JR, "Inexpensive Laser Diode Pulse Generator for Optical Waveguide Studies," Rev. Sci. Instrum., v 45, no 1, January 1974